THE PERFORMANCE OF EUCALYPTUS SPECIES IN HILL COUNTRY

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Abstract

Eucalyptus species, particularly stringybarks, which produce hard, durable wood are potentially useful in New Zealand, but most species are site sensitive. Twelve species (*E. agglomerata*, *E. baxteri*, *E. botryoides*, *E. cladocalyx*, *E. globoidea*, *E. microcorys*, *E. muelleriana*, *E. nitens*, *E. obliqua*, *E. pilularis*, *E. regnans* and *E. saligna*) were compared on four hill country microsites; upper and lower slope on sunny and shady aspects. Assessments included survival, foliar macro-nutrients, diameter at breast height (DBH), height, stem form, basic wood density and health to age 5 years. Site monitoring included solar radiation, temperature, rainfall and exposure. Foliar nutrients were strongly influenced by species and moderately influenced by microsite. Inter-nutrient and nutrient-growth correlations were identified and discussed. Subgeneric differences in nutrient profile were analysed with the aid of principal components analysis. Solar radiation and temperature were seasonal on both aspects but higher on the sunny face than the shady. Aspect differences were moderate, being greatest in the winter and least in the summer. A strongly seasonal growth pattern resulted, maximum DBH and height increments occurring in the spring and summer respectively. Growth was least in the winter. Seasonal and aspect effects on growth were related to solar radiation. Height and DBH (5 years) were significantly higher on the sunny face than the shady in all species. Slope position did not influence height but DBH on the lower slope was less than on the upper. Aspect had little influence on basic wood density and form. Species differed in growth, form and basic density. *E. nitens* was the most productive species but basic density was low. Conversely, density was highest in *E. cladocalyx*, among the least productive species. The stringybarks were intermediate in growth, form and density. The relationships between growth, form, density and environmental factors were explored with canonical correlation. Two species (*E. botryoides* and *E. saligna*) were adversely affected by possum browsing and infection by a leaf gall wasp (*Ophelimus eucalypti*). Discussion of the results includes consideration of the merits of assessments of relatively young trees as well as implications for tree growers.

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Chapter 1

Introduction

The New Zealand forest industry is unique in that it is almost completely reliant on plantation forests utilising exotic species, around 90% of which is *Pinus radiata*. The majority of the plantation area is intensively managed, including tending operations such as thinning and pruning to produce saw logs, both pruned and unpruned with rotation length generally less than 30 years. In many other countries plantations are typically managed to produce high volumes of pulp logs utilising high stocking rates and short rotations.

P. radiata is a medium density softwood which has endeared itself to generations of New Zealand foresters because of its good growth rates, generally good site tolerance, ease of management and responsiveness to management (Clifton 1990). It is a very versatile species being used in a wide range of applications including fibre for newsprint and fibre board, plywood, framing and construction timber, as well as furniture (Maclaren 1993). However, *P. radiata* is not a satisfactory species for all end uses (Harris 1984). Important deficiencies include low natural durability requiring treatment with chemical preservatives in situations where long term service is required, particularly in exterior situations but also in those situations where there is a risk of occasional exposure to moisture. The wood is not particularly attractive, being pale and bland, so it is not regarded as a premium wood for end uses where appearance is important, such as furniture and joinery. Being a medium density softwood means that it is relatively soft (Harris et al 1995) and therefore more susceptible to damage from general wear and tear when used for furniture compared to hardwoods such as European oak (*Quercus robur*). Although regarded as a site tolerant species there are sites for which *P. radiata* is not suited, for example those with significant risk of snowfall. In addition to these deficiencies there is concern over New Zealand's dependence on a single species. The arrival of pests and diseases from overseas capable of seriously damaging *P. radiata* could rob the forest industry of one of its most important competitive advantages.

The opportunity for alternative species (to *P. radiata*) has long been recognised. Burdon and Miller (1995) categorised potential alternative species into three groups.

i) Special purpose species: Species that produce wood with characteristics not available with *P. radiata* such as natural durability, hardness and high visual appeal.

ii) Extreme site species: Able to occupy sites not suitable for *P. radiata.*

iii) Contingency species: Capable of replacing *P. radiata* if production of that species became unviable.

There is minimal interest in alternative species particularly in the corporate forestry sector. The reluctance of this sector to move away from *P. radiata* reflects the inherent disadvantages of alternative species: Longer rotations, lower productivity and higher growing costs (Wilcox 1993). Despite this however, significant areas of species other than *P. radiata* are being established in some areas. For example, Douglas fir (*Pseudotsuga menziesii*) is being planted in the South Island high country, an environment not suited to *P. radiata*, and *Eucalyptus nitens* is being planted in the Bay of Plenty and Southland regions, primarily for the production of hardwood pulp (Neilson & Buckleigh 2002). However, despite the strong advocacy of alternative species, including *Eucalyptus*, by groups such as the New Zealand Farm Forestry Association (Barr 1996), the area being planted remains small and fragmented (Ministry of Agriculture and Forestry 2002; Maclaren 2005).

The *Eucalyptus* genus includes several species with considerable potential as alternatives to *P. radiata* in the special purpose, mostly from the *Monocalyptus* subgenus, and the contingency categories, mostly from the *Symphyomyrtus* subgenus (Burdon & Miller 1995; Barr 1996). Some of these species produce wood which is hard, strong, and of high natural durability while others produce decorative wood or are potentially very productive species (Menzies 1995). Eucalypts are generally very site specific; consequently appropriate siting is crucial for success with many potentially useful species (Wilcox 1993; Burdon & Miller 1995). Of particular interest are a few species from the stringybark group (*Monocalyptus*), which, in addition to their good wood characteristics, also suffer less from distortion of sawn timber, a problem with many hardwood species caused by tension wood (Menzies 1995).

Plantation forests in New Zealand were originally established on land not required for pastoral agriculture, for example cobalt deficient soils on the Central Volcanic Plateau, however expansion of the plantation area is now occurring through conversion of low value pastoral land, mostly steep hill country, to forestry (Maclaren 1993). A characteristic of hill country is heterogeneity mainly resulting from the influence of slope aspect, slope gradient and slope position on solar radiation which in turn affects air and soil temperature, soil moisture and soil fertility (Lambert & Roberts 1976; Radcliffe & Lefever 1981). These topographical differences produce a mosaic of microsites which have a significant influence on botanical composition and productivity of hill country pastures (Gillingham & During 1973; Lambert 1977).

As a group the eucalypts are generally intolerant of environmental conditions to which they are not adapted (Johnson & Wilcox 1989; Hocking 1995; Barr 1996). Many potentially useful species introduced to New Zealand are limited by temperature, particularly the occurrence of frost (Wilcox et al 1985; Wilcox 1989; Barr 1996; Shelbourne et al 2000b). This resulted in guidelines suggesting that frost sensitive species are only suitable for northern North Island regions (Forest Research Institute 1984). However, slope aspect can have a large influence on key environmental factors such as temperature. For example the effect of aspect on radiation and temperature may be the same as up to 9° of latitudinal displacement (Radcliffe & Lefever 1981), equivalent to about 1000 km. These aspect effects are greatest at the middle (New Zealand) latitudes (Holland & Steyn 1975). New Zealand (Bathgate et al 1993) and overseas (Lee & Sypolt 1974; Ares & Marlats 1995) research has found that microsites can significantly influence tree growth. There has been little research on the influence of microsites on tree growth in New Zealand, particularly with eucalypts. Observations in New Zealand suggest that some eucalypt species are affected by aspect, performing best on north facing slopes (Hocking 1995). Overseas research has shown that aspect and slope position can have a large influence on the natural distribution of *Eucalyptus* species (Brunori et al 1995) as well as growth of plantation eucalypts (Austin et al 1997). This suggests that blanket advice which does not consider the effect of microsite is inappropriate.

In 2000 New Zealand imported 13,000 m^3 of sawn hardwood timber, mostly tropical hardwoods, but 2,000 m^3 of this was eucalypt timber (Ministry of Agriculture and Forestry 2001). There is an immediate opportunity to substitute New Zealand grown eucalypts for much of this imported timber and in the long term replace all imported tropical hardwood timber as well as develop export opportunities (Wilcox 1993). However the current lack of resource means that demand will outstrip supply in the foreseeable future (Davies-Colley 1995). A major reason for the limited *Eucalyptus* resource is a lack of knowledge on all aspects of the husbandry of alternative species and, as a consequence, the reluctance of growers and investors, to make a major commitment to them, a situation that can only be remedied by research and experience. Priorities for eucalypt research include refining the list of potentially useful species (Burdon & Miller 1995) and addressing the question of optimal species siting, including the influence of microsite on growth, form and wood properties (Wilcox 1993).

The performance of 12 *Eucalyptus* species, four from the *Symphyomyrtus* subgenus, one from the *Nothocalyptus* subgenus and seven from the *Monocalyptus* subgenus, in Manawatu hill country will be assessed. The hypotheses for this study are that topographic features such as aspect, slope position and slope angle influence the relative performance (growth, stem form and wood characteristics) of different *Eucalyptus* species.

The specific research objectives for the study are:

- To identify the factors which characterise hill country microsites including temperature, solar radiation, nutrient availability and exposure.
- To determine the influence of aspect and slope position on the performance (establishment, early growth, stem form, pest/disease incidence, foliar nutrient concentrations and basic wood density) of 12 *Eucalyptus* species on different hill country microsites.
- To compare the performance of species from different subgenera
- To investigate the interrelationships between tree growth, stem form, basic wood density and environmental factors, such as solar radiation, foliar nutrient concentrations, pests and exposure, and the influence of microsite and subgenus on these relationships.
- To investigate the potential for using basic wood density measured in young trees to predict wood density in older trees of the same species on different sites.

The thesis includes a review of literature (Chapter 2), followed by a description of the trial site, species, establishment, tree assessments, site monitoring and statistical analyses (Chapter 3). Chapter 4 presents results from climatological monitoring including solar radiation, temperature, rainfall and exposure. Issues arising during the establishment phase of the trial, including survival and pest problems, are outlined in Chapter 5. The results of foliage analysis carried out at 2.5 years of age are presented in Chapter 6 while the main body of results, including growth, form, wood density and pest and disease issues are presented in Chapter 7. Chapter 8 presents a short analysis of the relationships between environmental factors, particularly solar radiation and growth. Chapters 6, 7 and 8 include some detail of methodology specific to individual sections. Methodology is presented here rather than in Chapter 3 for reasons of continuity and coherence. A comprehensive discussion is included in all results chapters. The final discussion (Chapter 9) integrates the results from previous chapters and considers the broad implications. Conclusions are also presented in Chapter 9.

Chapter 2

Review of Literature

2.1 Introduction

The literature on *Eucalyptus* classification, biology, ecology and silviculture is extensive however this review will initially briefly survey the environmental factors which influence the distribution of eucalypts; the probability of successful exploitation of *Eucalyptus* in plantations as exotics is strongly linked with the ability to match species to sites with similar environmental conditions to those of the native range of each species. The experience with eucalypts overseas will also be briefly covered: Rather the emphasis will be on New Zealand experience in the production of sawlogs, an uncommon objective in the majority of exotic eucalypt plantations. Factors influencing the probability of successful afforestation with eucalypts, are reviewed.

2.2 *Eucalyptus* classification

The *Eucalyptus* genus is large containing more than 600 recognised species, almost all of which are endemic to Australia (Pryor & Johnson 1971), dominating the natural vegetation in virtually all Australian climatic zones apart from very high rainfall and very arid areas (Pryor 1976). Most *Eucalyptus* species are subject to moisture deficits for significant parts of each year and in response to this produce sclerenchyma tissue, which consists of two types of cells, sclereids and fibres, both of which have thick secondary walls and are usually dead when mature. Their role is to provide mechanical support (Taiz & Zeiger 1998). It confers an ability to endure long periods of wilting without permanent damage. Consequently, *Eucalyptus* species are known as sclerophytes (Pryor 1976).

Classifications of the *Eucalyptus* genus and other genera of the Myrtaceae family are ongoing but at times complicated by the ability of many species to hybridise. The classification of Pryor and Johnson (1971) utilised an aggregative approach which grouped species using different criteria including morphological and genetic. They grouped species into subgenera which were genetically distinct, each subgenus containing species unable to hybridise with a species from any other subgenus. Some subgenera were further divided into sections, series, subseries, superspecies, species and subspecies. Subsequent discoveries and reclassification using a wider range of characteristics have resulted in the ongoing addition of recognised species (Florence 1996). Wilcox (1997) published a provisional catalogue of the eucalypts which included the *Angophora*, *Corymbia* and *Eucalyptus* genera, based primarily on the work of Hill and Johnson (1991a; 1991b). His catalogue divided the *Eucalyptus* genus into seven subgenera with further division of the largest subgenera, *Symphyomyrtus* and *Monocalyptus*, into sections or groups. Of the 664 species included in the *Eucalyptus* genus all but 26 are contained in the *Symphyomyrtus* (504) and *Monocalyptus* (134) subgenera. At the other extreme two subgenera, *Idiogenes* and *Nothocalyptus*, are monotypic. *Nothocalyptus* is represented by *E. microcorys* and is among the species included in this study. Pryor and Johnson (1971) placed *E. microcorys* in the monotypic *Sebaria* section of *Symphyomyrtus*, consequently it is included in *Symphyomyrtus* for comparisons of subgenera throughout the thesis. The subgenera and groups are listed below (Table 2.1).

The classification of *Eucalyptus* species is of relevance to forest researchers assessing the performance of different species in different environments. Membership of a subgenus or group within a subgenus can provide useful indications of the merits of different species. For example it is well known that *Symphyomyrtus* species tend to be more site tolerant than those from the *Monocalyptus* subgenus or that species from the stringybark group generally produce wood with highly desirable physical characteristics (Zacharin 1978; Florence 1996).

Table 2.1 A list of the subgenera and groups of the *Eucalyptus* genus according to the suggested classification published by Wilcox (1997).

Subgenus						
Eudesmia	Nothocalyptus	Symphyomyrtus	Gaubaea	Monocalyptus	Idiogenes	Telocalyptus
		Tingleria		Rubiginosae		
		Transversaria		Western Australian monocalypts		
		Michaelianae		White mahoganies		
		Red gums		Stringybarks		
		Tropical white gums		Blackbutts		
		Maidenaria gums		Ashes		
		Boxes		Peppermints		
		Ironbarks				
		Bisectaria				
		Dumaria				

2.3 *Eucalyptus* ecology

2.3.1 Natural distribution

The *Eucalyptus* genus dominates, or is a significant component of, the indigenous Australian flora in virtually all climatic zones, particularly in coastal areas, notable exceptions being very high rainfall zones, such as parts of Tasmania and north east Victoria where *Nothofagus* dominate, coastal Queensland where tropical hardwoods dominate, and the arid interior (Pryor 1976). They are the dominant species in the tall open forests, open forest, woodland and mallee forests. Tall open forest and open forest have previously been classified as wet sclerophyll forest and dry sclerophyll forest respectively. Tall open forests are generally found where rainfall is over about

1150mm, open forests between about 750mm to 1150mm, woodland between 400 and 750mm with mallee scrubland generally between 200 and 300mm. These rainfall zones may be modified by soil type, for example, mallee vegetation may be found on sandy soils with rainfall up to 400mm (Wood 1950). These vegetation zones are summarised below (Florence 1996).

i) Tall open forest: Dominant height between 30 and 60m with an understorey of ferns, small trees and other rainforest species (not sclerophylls).

ii) Open forest: Dominant height between 10 and 30m. Understorey often composed of grasses or shrubs on better soils or bare on poor soils. Open forests are the most important wood resource in Australia.

iii) Woodland: Dominant height between 5 and 10m. Trees widely spaced with an understorey of grasses. Extensively used for grazing.

iv) Mallee: Generally less than 5m in height. *Acacia* species begin to compete with *Eucalyptus* species for dominance.

Many species are highly adapted occurring in natural ranges as small as a few hectares (Pryor 1976) while some are present over a large geographic range (Williams & Brooker 1997). For example, *E. camaldulensis* occurs in all states except Tasmania (Boland et al 1984). Most typically though *Eucalyptus* species have a large geographic spread (Pryor 1976). This adaption has resulted in *Eucalyptus* species occupying climatic zones ranging from the wet and seasonally dry tropics, the wet temperate regions, the semi desert regions of the interior and the high altitude areas in the south east. On a macro scale distribution of individual species is controlled by two key environmental factors, rainfall and temperature which influence distribution at a regional level (Pryor 1976; Boland et al 1984) but with important modifying factors including soil fertility, altitude, fire and topography which influence local distribution (Adams 1996; Austin et al 1996).

2.3.2 Rainfall

There are strong contrasts between northern and southern areas of Australia in total rainfall and distribution. Rainfall in the north is strongly summer dominant followed by a long dry season whereas distribution switches to a marked winter maximum in the southern most areas (Victoria and Tasmania). The summer dominance in the north is due to the monsoonal influence which generally reaches as far south as the Tropic of Capricorn and in coastal areas down to northern New South Wales. South of the Tropic summer tends to be dry. Conversely, during the winter high pressure systems dominate the tropical areas producing little rain (Leeper 1950). Rainfall is predominantly winter in South Australia and the south west of Western Australia. Distribution is reasonably uniform in mid latitude areas (Turnbull & Pryor 1978; Florence 1996). Rainfall is highest in coastal areas while the interior is typically very dry, the contrast being greatest on the inland and coastal sides of the Great Dividing Range (Pryor 1976). Superimposed on this general pattern is the recurring phenomenon of drought. Rainfall variability is lowest in those areas where winter rain tends to dominate with coefficients of variation for rainfall generally less than 20%. This is lower than the variation typically found in other parts of the world with similar rainfall, and increases towards the north and inland areas where coefficients of variation are generally more than 40%, greater than comparable rainfall zones in other parts of the world (Leeper 1950).

In terms of their adaption to rainfall patterns *Eucalyptus* species can generally be divided up into three groups (Boland et al 1984).

i) Northern summer-rainfall group
ii) Southern winter-rainfall group
iii) South west group

Each group has a recognised centre of diversity being the North Kennedy pastoral district in northeastern Queensland, the Central Coast floristic region in southeastern Australia and the Darling botanical district in southwestern Western Australia for the summer-rainfall, winter- rainfall and south west groups respectively (Wardell-Johnson et al 1997). All three groups are centred near the coast with relatively high rainfall. The south west group experiences climatic conditions which are similar to those of the southern winter-rainfall group but are genetically quite distinct. This is almost certainly due to the geographic isolation of this group being separated from the winter-rainfall group by the Nullarbor Plain which is such a harsh environment that it acts as a barrier to the spread of *Eucalyptus* species (Pryor 1976).

2.3.3 Temperature

Temperature varies greatly according to latitude and altitude. Average temperature of the warmest (January) and coldest months (July), ranges between 30^0C (north) to 13^0C (Tasmania) and 24^0C (north) to 7^0C (Tasmania) respectively (Leeper 1950). The often narrow latitudinal limit of many *Eucalyptus* species is generally a response to temperature (Boland et al 1984). Similarly the altitudinal limit of *Eucalyptus* species is also largely a response to declining temperature with increasing altitudes (Austin et al 1983). However increasing altitude typically results in higher rainfall meaning that it may not always be easy to readily distinguish between the relative importance of different environmental factors (Pryor 1976). Examination of the morphological features of species, or provenances within species, found in different environments can help reveal the dominant influence (Pryor 1957). However average (or maximum) temperatures are not as important as minimum temperatures and in particular the occurrence of frost (Turnbull & Pryor 1978). Frost frequency can be high and frosts severe on high altitude sites where air drainage is poor, for example alpine plateaus in Tasmania and Victoria (Boland et al 1984; Florence 1996). In contrast, many coastal regions, including those in southern latitudes, are exposed to relatively few light frosts each year.

2.3.4 Soil fertility

Soil fertility, especially phosphorus (P), in much of Australia is comparatively poor as a result of a low nutrient profile in parent rocks and erosion and weathering over many millions of years (Boland et al 1984; Florence 1996). Eucalypts vary greatly in their fertility requirements (Pryor 1976); poor fertility has been suggested as the most important factor influencing the distribution of *Eucalyptus* species (Beadle 1962; Beadle 1966). Fertility may vary greatly due to edaphic factors such as parent material (Harrington & Humphreys 2004) and slope position (McColl 1969), fertility being higher on lower slope positions (Florence 1996) as a result of rain wash transporting soil and nutrients downslope, particularly after a fire when nutrient rich ash is vulnerable to such movement (Adams 1996). Soil fertility has a strong influence on the distribution of subgenera, often at the microsite level. Generally *Monocalyptus* species dominate eucalypt communities on low fertility soils whereas *Symphyomyrtus* dominate on higher fertility soils (Noble 1989). The sensitivity of different subgenera and species to soil fertility can be seen in some characteristic species-landforms distribution patterns. For example, in east coast hill country, where fertility typically increases from upper to lower slope, *E. globoidea* is primarily confined to upper slope positions, *E. pilularis* mid slope positions with *E. saligna*, or *E. maculata*, occupying lower slopes (McColl 1969; Neave et al 1995; Florence 1996). *E. globoidea* and *E. pilularis* are both *Monocalyptus* while *E. saligna* and *E. maculata* are both *Symphyomyrtus*.

2.3.5 Fire

Fire is an important component of natural eucalypt forest systems and most species are adapted to some extent to fire (Florence 1996) but it is not a significant factor influencing species-site matching in eucalypt plantations. Adaption to fire takes several forms: Epicormic buds arising from beads of leaf bud tissue which grow outwards at the same rate as diameter growth and which allows trees to quickly re-establish a leaf canopy after fire; thick and often fibrous bark, capable of protecting the trunk and lower limbs from the intense heat generated during fires; lignotubers in seedlings and young trees, which are less able to survive fire, containing many buds and a store of nutrients, allowing vigorous regrowth after fire (Jacobs 1955; Pryor 1976; Food and Agriculture Organisation 1979). Fire is probably more important in determining species succession than species distribution in most eucalypt communities (Florence 1996). Site factors such as soil structure and soil moisture, which may interact with fire incidence, are more important than fire in determining the distribution of rainforest and eucalypt forest (Barrett & Ash 1992). However, there are some exceptions to this. Some species, for example *E. nitens* and *E. regnans*, are very susceptible to fire and consequently restricted to sites where fires are uncommon or of low intensity (Wardell-Johnson et al 1997), for example high rainfall areas (> 1100 mm annually) as well as vallies and along water courses; sites which are less likely to become very dry (Pryor 1976; Boland et al 1984; Austin et al 1996).

2.3.6 Herbivores

Mammals, principally marsupials, birds and insects exploit eucalypts as a source of food, but the most important group are the insects which have adapted to feed on a variety of eucalypt tissues including foliage, sap, bark and wood (Florence 1996; Landsberg & Cork 1997). The beetles (*Coleoptera*), both adult and larvae, are the most important group of insects feeding on eucalypt foliage (Carne & Taylor 1978). Other important defoliators include the leaf minors, mostly caterpillars (*Lepidoptera*), and sap suckers, primarily scale insects (*Eriococcidae*) and lerps or psyllids (*Psyllidae*) (Landsberg & Cork 1997). These insects are capable of causing large scale dieback in eucalypt communities when multiple defoliation occurs (Florence 1996), particularly where the environment has been modified by human activity. For example, the use of fertilisers in agricultural regions may result in higher foliage nitrogen (N) content in eucalypt foliage which makes the foliage much more palatable to insects, resulting in greater defoliation (Landsberg 1990a, 1990b, 1990c). Other examples of human induced changes causing increased herbivory include salination which results in, so called, physiological drought, increasing the concentration of N compounds in the foliage and hence the palatability of foliage to insects (Marsh & Adams 1995). Eucalypts grown in plantations, which are often fertilised, may also be quite susceptible to defoliation by insects (de Little 1989). Natural causes of elevated N in eucalypt foliage and increased herbivore damage include drought (Marsh & Adams 1995). While insects also defoliate trees in unmodified forest systems, the growth habit of the eucalypts, in particular the presence of epicormic buds, means that they are generally able to recover quite quickly (Jacobs 1955).

The number and diversity of insect species found on *Symphyomyrtus* species are greater than that for *Monocalyptus* species (Noble 1989; Stone et al 1998). Part of the reason for this may be that *Monocalyptus* species are often found on lower fertility soils than *Symphyomyrtus* (Florence 1996). There are differences between the subgenera in the presence and concentration of leaf compounds known to influence herbivory. *Monocalyptus* lack formylated phloroglucinol compounds, which deter feeding by insects in *Symphyomyrtus* species but do contain high concentration of terpenes (Eschler et al 2000) which are also powerful inhibitors of insect herbivory (Edwards et al 1993). However, insects appear to be less responsive to foliar concentrations of polyphenols, for example tannins (Fox & Macauley 1977), than mammalian herbivores (Marsh et al 2003). Ironically, gypsy moth larvae (*Limantria dispar*), an exotic forest pest in Australia, may be a more serious pest of *Monocalyptus* species than *Symphyomyrtus* (Turnbull et al 1993) because it has evolved to consume conifer foliage which is naturally high in terpenes (Powell & Raffa 2003).

2.3.7 Covariance of environmental factors

Interpretation of the influence of individual factors, whether edaphic, climatic or biotic, on the distribution and productivity of eucalypts is complicated by correlations among the factors. For example, solar radiation, which is strongly influenced by latitude on a regional scale and by aspect on a local scale, may be significantly correlated with the distribution of eucalypt species (Kirkpatrick & Nunez 1980) but radiation may be considered an alternate for other critical environmental variables, such as temperature and soil moisture content (Kumar & Skidmore 2000). Similarly, altitude has a strong influence on temperature and rainfall but relationships between topographic and climatic variables may differ. For example, Pyrke & Kirkpatrick (1994) found that the relationship between altitude and temperature was close to linear whereas that between altitude and rainfall was not. The nature of competing vegetation also results in modification of several environmental factors including radiation, soil moisture and soil fertility (Bowman & Kirkpatrick 1986). Attempts to model the distribution and the interactions between different *Eucalyptus* species using information on environmental variables associated with different species have been carried out using a variety of modelling techniques including environmental niche presence-absence models as well as empirical and process or mechanistic models; these models are constrained by inadequate biological information (Austin et al 1997).

2.4 Eucalypts as exotics

In 2000 the total global *Eucalyptus* plantation area was estimated at about 17.9 million ha (Food and Agriculture Organisation 2001), making the genus among the most important group of plantation species and almost certainly the most important for hardwood plantations. Eucalypt plantations are mainly utilised for industrial wood, primarily as a source of hardwood fibre for the pulp and paper industry (Florence 1996), which typically are able to economically utilise logs with small end diameters down to 10 cm, whereas very few plantations are managed for sawlog production (Food and Agriculture Organisation 2001). One of the reasons for this is the growth habit of many eucalypt species, which results in mean annual increments (MAI) (m^3/ha) peaking at a relatively young age (Florence 1996). For example in South Africa (*E. grandis*) mean annual increment may peak at about age 10 years while in Portugal (*E. globulus*) it may peak at about 14 years (Food and Agriculture

Organisation 1979). These peak MAI ages are young compared to, for example, *Pinus radiata* plantations grown for saw logs in New Zealand, which may not have reached peak MAI by clearfell age at around 28 years (Ministry of Forestry 1996). The intolerance of eucalypts to competition and shade has resulted in the evolution of growth habits which gives them the capability of very rapid growth during the early sapling and pole stages, enabling them to quickly utilise canopy gaps and compete for space after forest modification, by fire, for example (Jacobs 1955). However when trees mature their growth habits change; crowns become spreading as new branches are increasingly produced from existing branches rather than the main stem and height growth declines. The availability of saw logs from local natural forests or the ability to grow other plantation species which produce saw logs of greater value than *Eucalyptus*, for example teak (*Tectona grandis*) and mahogany (*Swietenia spp.*) in tropical climates and black walnut (*Juglans nigra*) and oak (*Quercus spp.*) in temperate climates (Food and Agriculture Organisation 2001) also reduces the incentive to grow *Eucalyptus* plantations for sawlogs. In addition the problems with tension wood causing internal checking and distortion of sawn timber, particularly in the more productive species, is a significant disincentive for sawlog production (Haslett 1988a; Haslett 1990).

Almost all of the important eucalypt species grown as exotics are members of the *Symphyomyrtus* subgenus (Florence 1996; Food and Agriculture Organisation 2001). *E. globulus* is the most important species in cooler regions while *E. grandis* is dominant in warmer regions. Other important species include *E. urophylla*, one of the very few species not native to Australia, which is commonly planted in tropical regions, for example Brazil (Boland et al 1984) and *E. camaldulensis*, which is a commonly planted species in many monsoonal regions, particularly Central America (Fryer 1996), mostly due to its tolerance of seasonal drought, typical of the monsoonal tropics (Wilcox 1997). *Monocalyptus* species utilised for plantations include *E. regnans*, which has been planted in New Zealand (Poole & Fry 1980) and Australia (Boland et al 1984). New Zealand is one of the few countries where use of *Monocalyptus* species as exotics have been successful, probably because the rainfall and temperature environment is similar to that of many areas of south east Australia, from where most species planted in New Zealand originate (McWhannell 1960).

2.4.1 Countries other than New Zealand

Eucalyptus plantations are an important component of the forest industries of many countries, particularly in Asia and Central and South America; over 200 different species have been assessed as exotics (Zacharin 1978). Their utilisation in plantations for wood fibre production has been far greater in countries other than Australia, the earliest transferals, initially for ornamental purposes in Europe, occurring soon after Europeans first arrived (late 1700's) in eastern Australia (Pryor 1976). Eucalypts planted outside their natural range in Australia can also be included under this heading. For example, significant areas of *E. globulus*, a species found naturally in coastal Tasmania and Victoria, have been planted in Western Australia, well outside these areas, and consequently can be regarded as exotic in that State (Boland et al 1984; Florence 1996). Eucalypt plantations have become a major source of wood fibre in Australia, despite the vast areas of natural eucalypt forests available for exploitation (Turnbull et al 1993). In common with other regions of the world, the overwhelming majority of eucalypt plantations in Australia are also *Symphyomyrtus* species, mainly *E. globulus* and *E. nitens* (Turnbull et al 1993; Florence 1996). *E. globulus* is probably the preferred species in most situations because it has higher basic density than *E. nitens* (Boland et al 1984) making it more attractive to pulp mills because high density mean a greater weight of pulp can be processed in a given period of time (Fry 1983). *E. nitens* is mostly grown on cold sites (often high altitude) where frosts would probably kill *E. globulus* (Turnbull et al 1993).

Initially the area planted in eucalypts was modest but utilisation as a source of hardwood fibre accelerated after WW II and by 1961 the total volume of eucalypt fibre produced outside Australia surpassed that of Australia (Food and Agriculture Organisation 1979). The largest resource is found in Asia and South America, which in 2000 had 11 million and 4.8 million ha respectively; the productivity of these plantations varies tremendously depending intensity of management and on site quality, which is determined by a range of edaphic and climatic factors (Food and Agriculture Organisation 2001). The range in mean annual increments of the main *Eucalyptus* species utilised for hardwood fibre production is detailed in Table 2.2. Equivalent information for some of the major softwood species is provided for comparison.

Table 2.2 Range of mean annual increments (MAI) (m^3/ha) for plantations of the major *Eucalyptus* and *Pinus* species (adapted from Food and Agriculture Organisation 2001).

		MAI
Genus	Species	
Eucalyptus		
	E. camaldulensis	15 - 30
	E. globulus	10 - 40
	E. grandis	15 - 50
	E. saligna	10 - 55
	E. urophylla	20 - 60
Pinus		
	P. patula	8 - 40
	P. radiata	12 - 35

When good site quality is combined with intensive management, which may include pre planting cultivation, weed control, irrigation and the use of fertilisers, mean annual increments of 50 m^3/ha or more are expected in commercial plantations of the more productive species, for example *E. grandis* in Brazil (Food and Agriculture Organisation 1979).

Successful afforestation with eucalypts has generally only resulted from accurately matching site characteristics, particularly total rainfall, rainfall seasonality, fertility, and temperature, with species requirements (Herbert 1996). Where species or provenances are not appropriately sited the outcome can include complete failure or extremely low production (Food and Agriculture Organisation 1979; Florence 1996). The probability and severity of frost are particularly important in determining the suitability of a species, or provenance, for a particular site (Turnbull & Pryor 1978; Zacharin 1978). Climate mapping may be used to help identify sites suitable for different species and provenances (Booth 1990; Booth et al 1994). However in many regions of the world, especially underdeveloped, lack of information on climate resulting from the scarcity or absence of meteorological data has made the development of climate models which are able to predict climatic variables such as annual rainfall, dry season length and mean, maximum and minimum temperature from topographic variables such as latitude, longitude and altitude, and whatever meteorological information exists, problematic (Yan Hong et al 1996; Fryer 1996). Climatic mapping is also a useful tool in developed countries (Booth 1996). Growth modelling can then be used to predict performance of different species on different sites using the information obtained from climatic mapping and knowledge of tree growth obtained from scientific research as well as experience from local growers (Hackett 1996). Such models are mostly empirical, but process based models based on predictions of interception of solar radiation and the efficiency of conversion into biomass in different eucalypt species and under different environmental conditions have been developed (Sands 1995; Sands 1996). Extending these models to include information gleaned from satellite images of regional vegetation health and vigour allows estimation of current production using process models (Payn & Thwaites 1996). Coops et al (1999) found that there was a good relationship ($r^2 = 0.82$) between measured wood production in forests (including *Eucalyptus*) in Australia and New Zealand and net primary production in these forests predicted by the 3-PG model (physiological processes predicting growth).

Although eucalypts are adapted to a wide range of environmental conditions none are adapted to climates where ground freezes during the winter, effectively excluding them from high latitudes areas, almost all of which occurs in the northern hemisphere, about 45° in continental regions but up to 56° in maritime climates, for example Britain and Ireland (Pryor 1976). The global experience with planting *Eucalyptus* species not adapted to hard frosts in areas where hard frosts occur is that mortality can be very high, particularly when trees are young (Food and Agriculture Organisation 1979; Florence 1996). There are many examples from overseas and New Zealand of trials which have recorded high losses due to frosts. For example, Johnson & Wilcox (1989) experienced 100% death rates in 13 of 21 species being evaluated on a high altitude site (920 m) on the North Island Volcanic Plateau. The only species with acceptable survival were those originating from high altitude zones in south east Australia (eg *E. nitens* and *E. delegatensis*). Similarly Shelbourne et al (2000b) were forced to abandon a trial of *E. muelleriana* provenances at Omataroa, near Whakatane, in the Bay of Plenty due to severe frost damage. There may also be variation in frost resistance due to provenance (Rook et al 1980; Wilcox et al 1985).

The adaption of different species to annual rainfall influences performance when planted as exotics. Species adapted to high rainfall will generally fail in low rainfall environments but species adapted to low rainfall will grow when planted in high rainfall zones, though usually not as well as species adapted to high rainfall (Turnbull & Pryor 1978). Rainfall pattern can also influence the probability of success when planting eucalypts as exotics. Most species adapted to predominately winter rainfall areas do not generally perform well when planted in regions with a predominately summer rainfall, but the reverse situation is not necessarily true (Pryor 1976). Species originating from winter rainfall areas which have been planted in summer rainfall environments, such as *E. globulus* and *E. nitens*, have generally not been successful (Turnbull & Pryor 1978) but species originating from summer rainfall areas have been successfully planted in winter rainfall environments, for example *E. saligna* and *E. grandis* (Florence 1996). The most versatile species is probably *E. camaldulensis*; provenances from both winter and summer rainfall areas are available (Boland et al 1984). These examples of migrant eucalypts able to adapt to different rainfall patterns are all *Symphyomyrtus* species. In contrast, *Monocalyptus* species have generally displayed a poor ability to adapt to different rainfall patterns, particularly drought, which differ from those of their native range (Food and Agriculture Organisation 1978).

2.4.2 New Zealand experience

Eucalypts were planted in New Zealand as early as the 1830's (Barr 1996). More than 100 *Eucalyptus* species have been introduced to New Zealand, the majority originating from Australia's south east, Tasmania, Victoria and southern New South Wales (Menzies 1995) which have rainfall and temperature regimes closer to those in New Zealand than other areas of Australia (Wilcox 1980) and therefore more likely to be adapted to local conditions (Food and Agriculture Organisation 1979). Very early plantations were dominated by *E. globulus* or Tasmanian blue gum and to a lesser extent *E. viminalis* (Ellis 1925), an unfortunate event because it is not well adapted to climatic conditions in many regions of New Zealand and it was attacked by *Eriococcus coriaceus*, a scale insect, which killed many trees (Weston 1957). Later on both *E. globulus* and *E. viminalis* were attacked by *Paropsis charybdis* (*Eucalyptus* tortoise beetle) which also resulted in poor growth and high mortality (Forest Research Institute 1990). The early experiences with *E. globulus* resulted in a jaundiced view of *Eucalyptus* in New Zealand and there was little further interest in them until the 1960's (Fry 1983). Prior to then most planting was done on farms rather than in large State or private forests (Weston 1957), in contrast to the situation for *Pinus radiata*, by that stage the dominant plantation species in New Zealand. However, by the 1960's the continuing demand for hardwood pulp coupled with declining supply of native hardwoods, particularly tawa (*Beilschmiedia tawa*) (Henry 1957) resulted in significant areas being planted, mostly of *E. regnans* and *E. fastigata*, on the Volcanic Plateau near Tokoroa (Poole & Fry 1980).

Renewed interest in eucalypts in New Zealand was initially mostly focussed on the ash group, in particular *E. delegatensis* (Wilcox, 1979a; Adams 1981), due to its tolerance of hard frost (down to - 14°C) (Forest Research Institute 1984). Other members of the ash group, including *E. fastigata*, *E. obliqua* and *E. regnans* as well as other potentially useful species, mostly *Symphyomyrtus*, were evaluated at sites in the North (Johnson & Wilcox 1989) and South Islands (Wilcox et al 1985). Some trials also included provenance tests. Although the ashes were quite productive in some situations interest in them waned because of the great difficulty with tension wood during milling and seasoning (Haslett 1990), an exception being the use of *E. regnans* for short rotation pulp production (Poole & Fry 1980). There was also some interest in the peppermint group in the 1970's (Wilcox 1979b). A number of peppermints were included in two large scale species evaluation trials in the Wairarapa region (southern North Island), albeit for evaluation of erosion control potential, but none proved to be particularly productive (Hathaway & King 1986; Bulloch 1991; Shelbourne et al 2002). By 1980 the total area of eucalypts in New Zealand was about 12,000 ha, only 1.5% of the area in *P. radiata* and mainly (90% of total area) comprised *E. regnans*, *E. fastigata*, *E. delegatensis* and *E. saligna* and mostly managed for pulpwood production (Fry 1983). Of these *E. fastigata* has become the 'best bet' in many areas of New Zealand because it has a low health risk, good site tolerance (frosts down to -10°C) and has acceptable appearance and strength (Nicholas 2005).

Other species, particularly *E. saligna* and to a lesser extent *E. botryoides*, were being recommended for warmer parts of the North Island, mostly based on farmer success with these species in Northland (Barr 1996) and growth monitoring of established stands, also in Northland (Williamson 1981). They had also performed well in trials on warmer sites (low altitude) on the North Island's Volcanic Plateau (Johnson and Wilcox 1989). The interest in these species arose because of the quality of the wood they produced. Both typically have pink heartwood which is attractive, hard and moderately durable (Mckenzie & Hay 1996). Other species which demonstrated promise in these trials included *E. nitens*. It was noted for its rapid established and early growth, as well as frost tolerance, but after the transition from immature to mature foliage growth began to suffer because of attack from the larvae of *Paropsis charybdis* (Wilcox et al 1985; Johnson & Wilcox 1989). It was regarded as potentially a useful species on cold sites and was already being planted on the Volcanic Plateau for pulp production (Lausberg et al 1995). However, the wood of *E.*

nitens was not of particular value, being relatively light, pale and not naturally durable (Haslett 1990), suggesting that its use may be limited to pulp production only (Lausberg et al 1995).

Ongoing difficulties experienced by millers sawing ash species due to tension wood (Haslett 1990) as well as the arrival of a series of new insect pests from Australia (Section 2.3.1.1), which mainly targeted *Symphyomyrtus* species, particularly the eastern blue gums, *E. botryoides* and *E. saligna* (Treeby 1997a & 1997b), and the unremarkable wood characteristics of *E. nitens* (Miller et al 1992) resulted in attention moving away from these species. Farm foresters in Northland began milling trees from the stringybark group, part of the *Monocalyptus* subgenus (Barr 1980; Barr 1996). The stringybarks, principally *E. muelleriana* and *E. pilularis*, had been identified as possibly useful for sawlog production in New Zealand because of the good reputation they enjoyed in Australia and New Zealand (Weston 1957; McWhannell 1960; Barr 1996) when utilised for railway sleepers, poles and cross arms for power and telephone lines as well as bridges and wharves (Boland et al 1984; Davies-Colley 1995; Barr 1996). However the stringybarks received little attention from researchers until the 1990's (Shelbourne et al 2003). In a paper presented to the combined conference of the Australian and New Zealand Institutes of Foresters Nicholas (1991) did not recognise any of the stringybarks as speciality timber species for farm sites citing lack of research and experience with them. Despite this though the research emphasis during this time was on the more productive *Symphyomyrtus* species, such as *E. nitens*, *E. fastigata*, *E. botryoides* and *E. saligna*, for use in short rotation pulp plantations (Low & Shelbourne 1999). There were though some early efforts to improve the New Zealand knowledge of stringybarks grown for saw logs; a stand of *E. muelleriana* was established at Athenree Forest, near Katikati in the coastal Bay of Plenty in 1961 by Harry Bunn (New Zealand Forest Service) (Wilcox 1998), unfortunately an uncommon example of good foresight.

Wilcox (1993) observed that sawlog production from *Eucalyptus* had very little emphasis internationally and that New Zealand could establish a niche for itself in this area. He also recommended that research on alternative species (other than *Pinus radiata*) be concentrated on species and localities which had a good likelihood of supporting commercial development. He suggested several stringybark species including *E. globoidea*, *E. muelleriana*, and *E. pilularis* and that regions likely to support these species were Northland (*E. muelleriana*, and *E. pilularis*), Wairarapa and Marlborough (*E. muelleriana*) and Bay of Plenty (*E. globoidea*). In 1993 the New Zealand Forest Research Institute initiated a programme to assess the performance of several stringybark species including *E. globoidea*, *E. muelleriana* and *E. pilularis*, as well as other species known to produce heavy, hard and durable wood (*E. cladocalyx*, *E. microcorys*). The programme included on farm evaluations, establishment of permanent sample plots in existing stands as well as species evaluation trials (Shelbourne et al 2000b; Shelbourne et al 2003).

2.4.2.1 Pests

A uniquely New Zealand experience with eucalypts has been the ongoing arrival of damaging insect pests from Australia. This aspect of the utilisation of eucalypts as exotics is a particular issue in New Zealand, probably because of our proximity to Australia (downwind), as well as the growing importance of Australia-New Zealand trade; many are more serious pests in New Zealand than in Australia, probably because they arrive unencumbered by antagonistic organisms (Withers 2001). This is well illustrated by *Ophelimus eucalypti* (leaf gall wasp), which, despite being a serious pest in New Zealand has not been reported in Australia (Withers et al 2000), indicating just how obscure some insect species may be in their native range.

Eucalyptus tortoise beetle (*Paropsis charybdis*) was one of the first serious pests of eucalypts in New Zealand, probably arriving in the late 1920's; Forest Service reports from the mid 1920's make no mention of it (Ellis 1925). A number of biological control agents were evaluated and one of these (*Enoggera nassaui*) was successfully introduced in the late 1980's, providing good control of *Paropsis* (Forest Research Institute 1990). This allowed the use of potentially very productive species, such as

E. nitens, which had previously suffered severe damage and consequently not recommended for planting (Wilcox et al 1985). A twist in this story occurred during the 2001-2002 summer when *Paropsis* reappeared. The cause was a hyper-parasitoid (*Baeoanusia albifunicle*) which was parasitising *Enoggera nassaui*. (Jones & Withers 2003). However, other parasitoids of *Paropsis* introduced in the 1980's, may potentially replace *Enoggera nassaui*. One of these, *Neopolycystus insectifurax*, is making little impression but the southern ladybird (*Cleobora mellyi*), rediscovered in the Marlborough Sounds (Satchell 2004) has been reintroduced to the North Island with some hope that it will establish and provide some control of *Paropsis* (Mansfield 2005).

The gall wasp (*Ophelimus eucalypti*) was first detected in Wellington in 1985 (Maclaren 1989). Biological control agents were investigated and it is apparently being parasitised by three wasp species but remains widespread on susceptible species throughout the North Island (Withers et al 2000). Other recent arrivals include the eucalyptus leaf-mining sawfly (*Phylacteopha froggatti*), first discovered in 1985 but which is now controlled by a parasitic wasp (*Bracon phylacteophagus*) (Faulds 1992), the brown lacy lerp (*Cardospina fiscella*), spotted gum psyllid (*Eucalyptolyma maideni*), which primarily attacks *Eucalyptus maculata*, both discovered in Auckland in 1996 and gum leaf skeletoniser (*Uraba lugens*), a potentially serious defoliator of eucalypts, which was discovered at Mount Maunganui in 1997 (Treeby 1997a) but eradicated from that area (Hocking 2003a). A subsequent discovery of gum leaf skeletoniser was made in Auckland in 2001 and, although eradication efforts were initiated, remains present in the Auckland area. Biological control agents are being assessed (Ridley 2004).

These pests have targeted the eastern blue gums, *E. botryoides* and *E. saligna*, in particular and, in the case of gum leaf skeletoniser, one of the stringybark species, *E. pilularis* (Treeby 1997b). Damage has been severe and widespread in *E. botryoides* and *E. saligna* and has resulted in a general recommendation that these species are no longer planted in New Zealand (Shelbourne et al 2003).

2.4.2.2 Genetic improvement

Genetic improvement of *Eucalyptus* in New Zealand has primarily focussed on identifying suitable provenances of a range of species regarded as having potential use for pulp, sawlog and land stabilisation, and has changed over time with local experience. Of the species which have, or are currently regarded as, being of potential use for sawlogs, provenance testing has been carried out for *E. botryoides* (Hathaway & King 1986; Low & Shelbourne 1999; Shelbourne et al 2000a, 2000b), *E. cladocalyx* (Hathaway & King 1986), *E. delegatensis* (Wilcox et al 1985; Hathaway & King 1986; Johnson & Wilcox 1989; King et al 1993), *E. fastigata* (Wilcox 1982b; Wilcox et al 1985; Hathaway & King 1986; Johnson & Wilcox 1989; Shelbourne et al 2000a), *E. globulus* (Wilcox et al 1985; Low & Shelbourne 1999; Shelbourne et al 2000a), *E. muelleriana* (Hathaway & King 1986; Shelbourne et al 2000b), *E. nitens* (Franklin 1980; Wilcox 1985; Hathaway & King 1986; Johnson & Wilcox 1989; Low & Shelbourne 1999; Shelbourne et al 2000a), *E. obliqua* (Wilcox et al 1985; Hathaway & King 1986), *E. pilularis* (Davies-Colley 1998), *E. regnans* (Wilcox 1982a; Wilcox et al 1985; Johnson & Wilcox 1989; Shelbourne et al 2000a), *E. saligna* (Wilcox et al 1982a; Hathaway & King 1986; Johnson & Wilcox 1989; Low & Shelbourne 1999; Shelbourne et al 2000a, 2000b) and *E. viminalis* (Wilcox et al 1985; Hathaway & King 1986; Johnson & Wilcox 1989). In addition family testing for traits such as growth and frost resistence has been undertaken in several species including *E. fastigata* (Wilcox 1982b), *E. muelleriana* (Shelbourne et al 2000b), *E. nitens* (Wilcox et al 1985; Hathaway & King 1986; King & Wilcox 1988) and *E. regnans* (Wilcox 1980; Wilcox et al 1985; Hathaway & King 1986; Shelbourne et al 2000a).

In many species significant differences between provenances for growth and/or form have been identified. For example, in *E. nitens* provenances from Victoria have generally performed better than those from New South Wales (Franklin 1980; Wilcox et al 1985; Bulloch 1991). In contrast, New South Wales provenances generally fared better than those from Victoria at Kaikohe, Northland (Low & Shelbourne 1999), the Victorian provenances suffering from an unidentified crown disorder and high mortality. It was suggested that the New South Wales provenances were better adapted to the relatively warm summer rainfall environment in Northland, conditions similar to those of northern New South Wales.

E. regnans provenances from Gippsland, Victoria have generally been found to have better growth than those from Tasmania or central Victoria but were more susceptible to frost damage (Wilcox 1982a). Provenances with the best frost resistance came from high altitude sites in Victoria and Tasmania. Interestingly, these results mirror those of Griffin et al (1982) in Australia, who also found that low altitude Victorian provenances had the best growth while high altitude provenances from Tasmania and Victoria had the best frost tolerance. However, some trials have found minor (Wilcox et al 1985) or no significant differences (Bulloch 1991) between *E. regnans* provenances representing the major provenance groups identified by Wilcox (1982a). A possible explanation for this is that on sites where frosts are generally light or moderate provenance differences in frost sensitivity are not expressed. This may be particularly important for assessments done at a young age when trees are more vulnerable to frost damage (Food and Agriculture Organisation 1979). Both of the above studies (Wilcox et al 1985; Bulloch 1991) were conducted on sloping ground at relatively low altitudes, site factors which tend to reduce the severity of frosts and also reduce the probability of out of season frosts (Burgess 1988), which can be particularly damaging to young eucalypts (Rook et al 1980). Provenance differences may take considerable time to manifest. For example, whereas Bulloch (1991) found no differences between *E. regnans* provenances at 12 years, Shelbourne et al (2003) did find significant differences between the same provenances in DBH and crown health at 22 years after re-measuring the same trial. The performance of trees of a number of species grown from seed collected from trees or stands growing in New Zealand has generally reflected the Australian origin of the original trees (Wilcox 1982a; Miller et al 1992).

Provenance differences in wood characteristics have also been found in New Zealand. Harris & Young (1980) noted provenance differences in basic density in *E. botryoides*, *E. pilularis* and *E. saligna*. Variation in wood characteristics, such as basic density and internal checking, between individual trees has also been found to be large, suggesting that there is also some scope for selecting and breeding to improve wood characteristics (Lausberg et al 1995). These authors found that the basic density of individual *E. nitens* ranged from 371-380 kg/m^3 to 531-540 kg/m^3.

Tree breeding programmes were initiated for *E. botryoides*, *E. delegatensis*, *E. fastigata*, *E. nitens*, *E. obliqua*, *E regnans* and *E. saligna* in the late 1970's (Wilcox 1980). Briefly, the major selection criteria were growth and form with frost resistance being additional criteria in *E. fastigata* and *E. regnans* and resistance to *Paropsis charybdis* (*Eucalyptus* tortoise beetle) in *E. nitens*. The extent of genetic improvement was limited to identification of the best provenances in some species but in *E. fastigata*, *E. nitens*, *E. regnans* and *E. saligna*, identification of superior families resulted in the establishment of seed orchards. In three species, *E. botryoides*, *E. regnans* and *E. saligna*, elite trees were used to provide grafts for clonal seed orchards. However, because of a change of emphasis away from species more suited to pulp production and towards higher value special purpose species, typified by the stringybark eucalypts (Burdon & Miller 1995), the early effort put into these species has not been maintained (Barr 1996).

2.4.2.3 Site

Recommendations for siting different eucalypt species in New Zealand have generally been broad, early assessments of sites suitable for different species focussing on specific regions but with some caveats in some regions which included geographic factors such as altitude (Weston 1957). Later, species-site recommendations were based on broad climatic regions rather than geographic regions. For example, the Forest Research Institute (1984) described three climatic regions and listed a number of species, under different end use regimes (decorative, strong and durable or fuel wood), suitable for each region. Regions were primarily defined by temperature; region one being 'warm' (mean annual temperature of 12.5^o C and maximum frost of -8^{o}C), region two being 'cool' (mean annual temperature of

10 - 12.5° C and maximum frost of -10°C), and region three being 'cold' (mean annual temperature of 7.5 - 10.0° C and maximum frost of -14°C). Only cold tolerant species and cold tolerant provenances in species with variable cold tolerance were suitable for the cold regions. The stringybark species were only recommended as suitable for the warm region. Frost tolerance has probably been the key criterion for determining suitable sites for different species (Revell 1980; Johnson & Wilcox 1989) but additional information, such as tolerance of drought, wet soils and wind, have supplemented frost tolerance limits (Forest Research Institute 1984; Nicholas 1991).

The expansion of the plantation forest industry in New Zealand requires afforestation of relatively unproductive pastoral land, primarily hill country (Knowles 1991; Thorrold et al 1998) which is typically a mosaic of microsites, the result of aspect and slope position differences in soil depth (Trustrum & De Rose 1987) and soil type (Pollock & McLaughlin 1986), and solar radiation and temperature (Lambert & Roberts 1976; Radcliffe & Lefever 1981). The influence of aspect on key environmental factors such as temperature can be substantial. For example, Radcliffe & Lefever (1981) found that the difference in mean temperature between sunny and shady aspects was equivalent to a latitudinal displacement of about 9°. To put this into perspective, the North Island of New Zealand extends over about 6° of latitude (NZ Meteorological Service 1983). A key feature of hill country influencing siting of different eucalypt species is the drainage of cold air during cool nights, greatly reducing the incidence and severity of frosts (Burgess 1988). A number of researchers and farm foresters have observed that many of the more frost sensitive eucalypts, such as the stringybarks, can only be grown in districts south of about Auckland on sloping ground, for example Bay of Plenty (Weston 1957) and Rangitikei (Hocking 1995).

The need to be more specific about siting of eucalypts, particularly the problem of microsite variation, has been recognised in New Zealand (Wilcox 1993; Nicholas 2005). Lack of knowledge on any aspect of forestry represents a risk which investors and growers need to take into account when considering forestry ventures. For alternative species such as the eucalypts, which are constrained by lack of knowledge as well as biological risks such as pests, risk becomes excessive, deterring investment (Maclaren 2005).

2.4.2.4 Management for sawlog production

The most important management objective for saw log production in New Zealand is the need to produce large diameter logs at harvest. The reason for this is that, being hardwoods, tension wood has the potential to cause considerable degrade and recovery losses during milling, drying and processing (Haslett 1988a). To help reduce the radial gradient in tension between the perimeter and centre of logs it is necessary to grow logs to large diameter (Figure 2.1); current recommendations are that minimum DBH at harvest should be 75 cm in most species (Forest Research Institute 1984b; Hay 1995). Another requirement is the production of large diameter logs, without greatly extending the rotation length. This is because long rotations reduce the rate of return on forestry investments leaving species with longer rotations at a disadvantage compared to *P. radiata* (Cavana & Glass 1985; Maclaren 2005). Consequently it is necessary to reduce final crop stocking rates to relatively low levels so that diameter growth remains unrestricted by competition for as long as possible. For example, growth models generated from permanent sample plot data in Northland and Bay of Plenty for *E. saligna* predict that at 40 years of age mean DBH at a final stocking of 100 stems/ha would be 69.4 cm whereas at 300 stems/ha mean DBH would be 41.5 cm (McKenzie & Hay 1996). Current advice on appropriate final crop stocking rates for eucalypts in New Zealand ranges between 100 to 200 stems/ha (Hay 1995; Barr 1996). Other requirements to help minimise tension wood are balanced crowns. Even spacing at final thinning is important for achieving this.

Growth stresses vary in different species. For example *E. botryoides* and *E. saligna* are regarded as high stress species whereas most of the ash species (eg *E. regnans*, *E. obliqua*) generally display intermediate growth stresses (Haslett 1988b). However, the stringybarks have a good reputation in Australia (McWhannell 1960; Shelbourne et al 2003) and this has also been the experience in New Zealand (Weston 1957; Davies-Colley 1995; Wilcox 1998), allowing for potentially good recovery of sawn timber during milling (Somerville & Gatenby 1996).

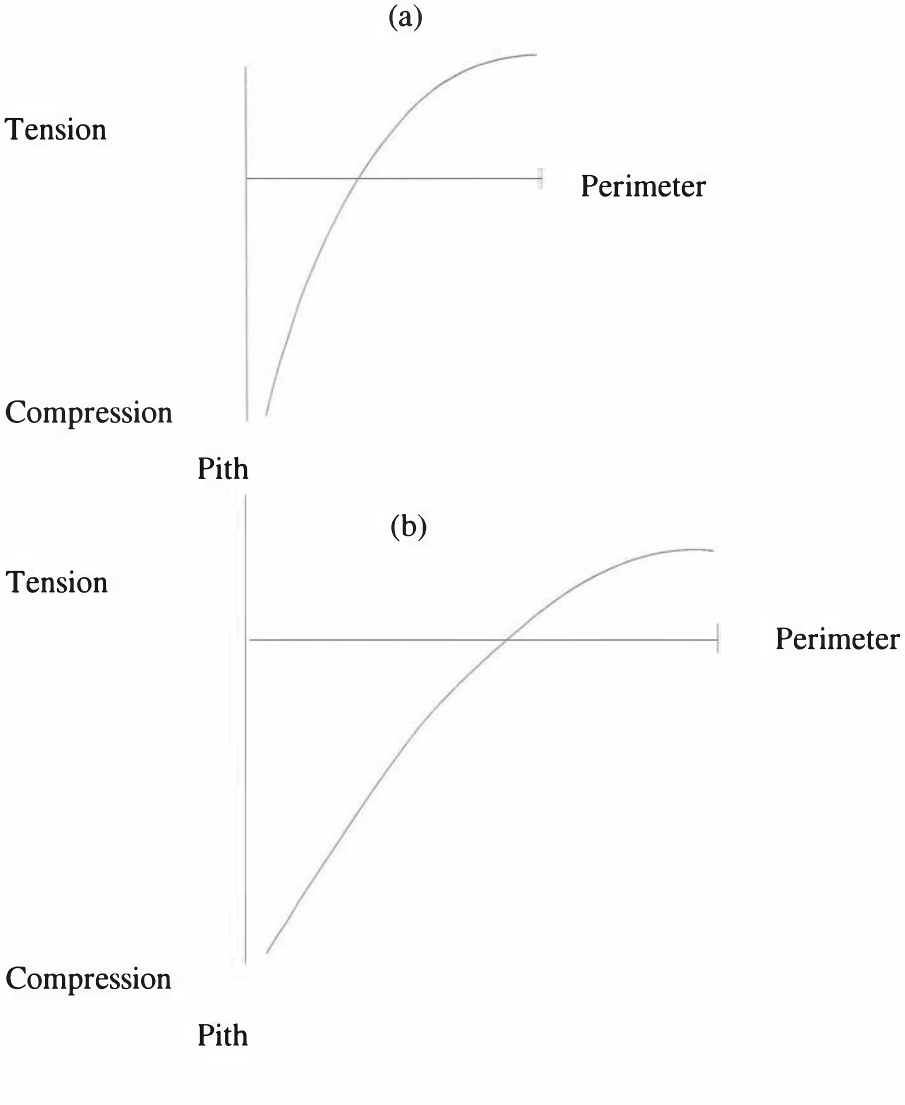


Figure 2.1 The influence of stem diameter on the tension gradient in (a) small and (b) large diameter eucalypt logs (Adapted from Haslett 1988b).

2.5 Summary

The *Eucalyptus* genus is large and diverse, containing seven subgenera, the most important being *Symphyomyrtus* and *Monocalyptus*. Collectively *Eucalyptus* species are capable of occupying and dominating virtually all other sites from warm, tropical, summer rainfall environments in the north to cold, alpine winter rainfall maximums in the south. Many different *Eucalyptus* species have been planted and evaluated in most parts of the world, including New Zealand, the major exception being high latitude areas where winters are severe. However, few species are grown on any scale. Globally, they are probably the most important genus for plantation hardwood pulp production. When intensively managed eucalypt plantations may be highly productive with, typically short rotations (< 15 years) in many countries. The corporate forestry sector in New Zealand has also focussed on the use of eucalypts for short rotation hardwood fibre. However, there has been a long tradition among many farm foresters in New Zealand of growing eucalypts for sawlogs, but with variable success. A major problem has been the extreme site sensitivity of many of the more useful species as well as provenance variation within species. Problems with tension wood have also plagued millers and end users.

Virtually all of the species which have succeeded as exotics within and outside Australia are from the *Symphyomyrtus* subgenus; they are generally more site tolerant, establish quickly with faster early growth, endearing them to plantation owners. Accordingly, the early emphasis in New Zealand was on *Symphyomyrtus* species and significant areas were planted for pulp production, particularly *E. regnans*. Other *Symphyomyrtus* species have been widely planted for sawlog production, particularly *E. botryoides* and *E. saligna* but a series of insect pest introductions from Australia has dented the reputation of these species. In contrast *Monocalyptus* species have been found to be more site sensitive and less productive, hence are rarely planted for industrial wood production. However, *Monocalyptus* species from the stringybark group are of interest in New Zealand for solid wood production because they possess highly desirable wood characteristics, including strength and natural durability. They are also much less susceptible to sawing problems resulting from tension wood and are less liable to defoliation by insects.

There has been some research on the siting of eucalypt species on a regional scale in New Zealand, mostly *Symphyomyrtus* species and ash species, however, research on potentially useful species, including the stringybarks, has been relatively limited. Of the stringybarks, *E. muelleriana* has been assessed in a few trials, mostly in Northland, but information on the performance of other stringybarks, such as *E. globoidea* and *E. pilularis*, is very limited and virtually absent for other potentially useful species. Very little research has been carried out on siting at a local scale or the influence of microsite variation in environmental factors, such as temperature, on eucalypt performance.

The foremost land resource available for afforestation in New Zealand is hill country, which is inherently variable, comprising of a mosaic of microsites resulting from variation in slope, soil and meteorological factors. Variation in microsite environment can be greater than that between distant regions. Juxtaposed with this is the strong intolerance of many potentially useful species to environmental conditions outside those of their native range. Knowledge of the performance of different species in different environments, including microsites, is essential if eucalypts are to become a significant component of the New Zealand forest industry.

Chapter 3

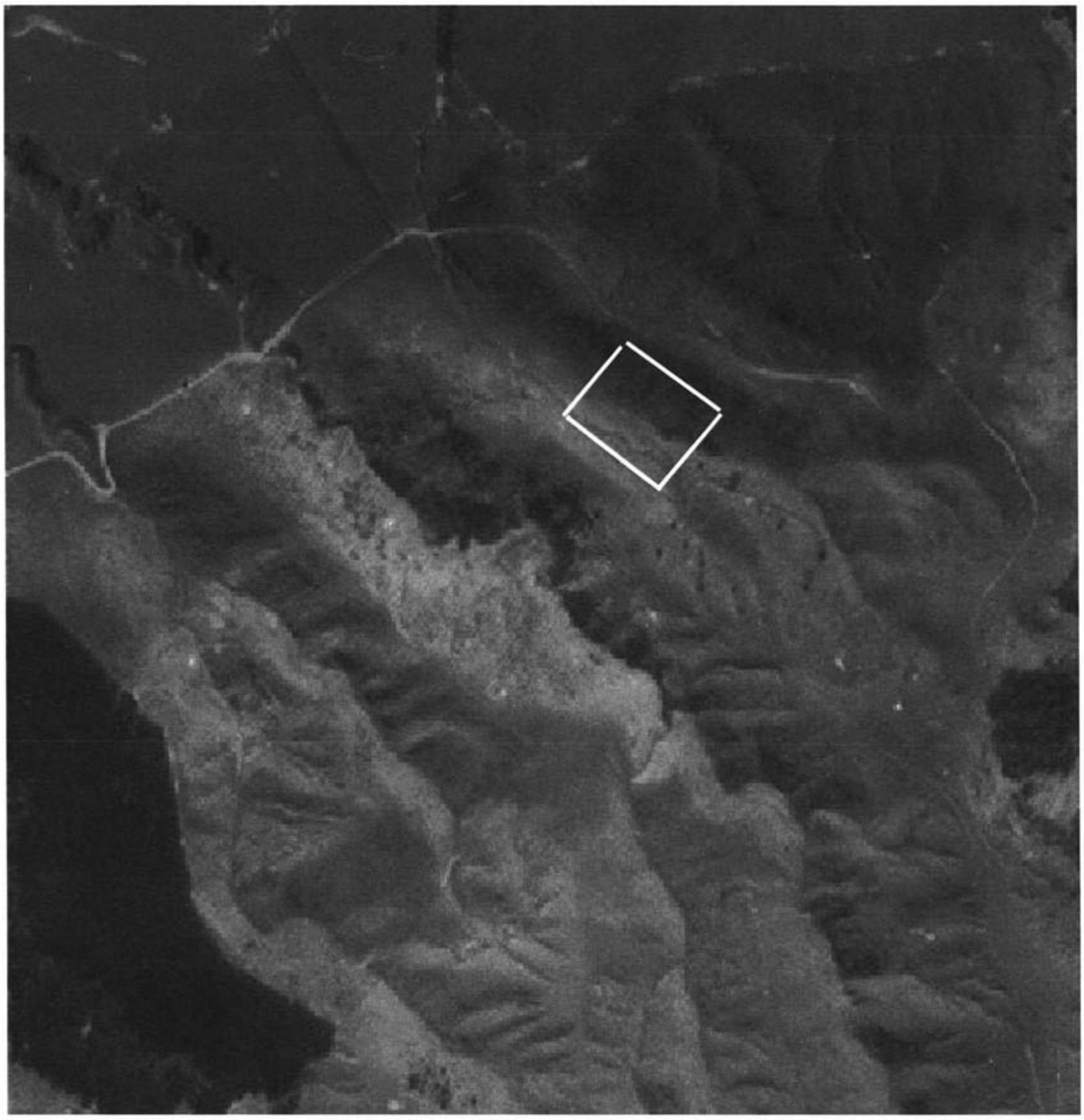
Study Site, Species and Methods

3.1 Introduction

This chapter describes the experimental site including location, soils, topography and climate. The selection of the *Eucalyptus* species evaluated, species characteristics and the source/origin of seed used to propagate planting stock, weed control, planting and management of the trial, tree assessment for growth and health, meteorological recording and statistical analyses are detailed. Subsequent chapters presenting results will provide additional specific methodology where appropriate.

3.2 Trial site

The trial site is located at Tuapaka, a hill country property owned and managed by Massey University, located approximately 5 km south of the Manawatu Gorge on the western flank of the northern Tararua Range (40° 20.14' South and 175° 44.66' East) and is accessed from State Highway 57. Tuapaka features two distinct landscapes: The front of the property comprises flat terraces formed from loess whereas the back of the property comprises a series of old marine benches, which form the hill country of the northern Tararua Range (Pollock & McLaughlin 1986). The terraces and the hill country are separated by an escarpment which has been incised by streams running off the hill country in a westerly direction resulting in the formation of gullies with sides facing north and south. The gully formed by one of these streams has been used as the trial site (Figure 3.1). The topography of the trial site is moderate to steep and altitude varies from about 80 (stream bed) to 140 m (ridge) above mean sea level.



Scale: ▬ = 100 m

Plate 3.1 An aerial photograph, oriented approximately north to south, of part of Tuapaka farm showing the approximate size and position of the trial site (rectangle). The upper left shows the flat terrace with a vehicle track at the bottom of the escarpment between the terrace and the old marine benches and examples of the dissecting streams. The contrasts between the north and south aspects are apparent in this view. The gully just south of the trial site is very steep with many bluffs and was planted in *Pinus radiata* in 1993.

3.2.1 Microsites

The topography of the trial site has resulted in a diversity of physical environments which can be categorised as distinct microsites. Differences in aspect, slope and altitude shape some of the key environmental factors influencing plant growth, such as solar radiation and temperature (White 1990). Aspect is probably the major geographic feature of hill country. Sunny aspects receive more sunlight and consequently have higher air and soil temperatures and lower soil moisture contents than shady aspects in most areas of New Zealand (Chapman & Macfarlane 1985; Scott et al 1985). Slope position also influences plant growth: Soil depths tend to be greater on lower slopes, a result of the downhill movement of soil from slip erosion (Pollock & McLaughlin 1986). Soil water holding capacity and fertility are reduced on upper slopes as a result and upper slopes are more exposed to wind (Hathaway 1986). Grazing animals also transfer nutrients from steep areas of a slope to areas where they find it more comfortable to rest and camp, usually flatter sites (White 1990).

The trial design used in this study incorporated slope position and aspect as treatments or factors, that is, the upper and lower slope on the sunny and shady face, four microsites in total.

3.2.2 Soils

Two soil types, Halcombe hill soils and Halcombe steepland soils, dominate the Tuapaka escarpment and the sides of dissecting gullies, (Cowie 1978). Hill soils range from 15° to 25° and steepland soils are typically found on slopes above 25° (Pollock & McLaughlin 1986). They originate from both loess and marine sediments, mostly sand, with gravel and stones (greywacke) also present throughout the profile. However, there has been considerable slip and tunnel gully erosion of these soils meaning that soil depth and profiles are extremely variable due to movement and mixing (Cowie 1978). The original vegetation was broadleaf forest cleared in the late

19th century to allow pastoral farming. Small areas of the lower marine terrace soils can be found on the ridges above the gullies, mostly Shannon silt loam which is formed predominately from loess.

Cowie (1978) described the Halcombe soils from undeveloped sites as having high base saturation but low phosphorus (P) reserves, making them quite responsive to P fertilisers. Both the surface and subsurface horizons are sandy in texture and contain a few stones. The subsoils are heavy silt loam in texture, compact, with many stones. The parent material typically lies at a depth of about 60 cm, ranging from sandy to silty in texture and is strongly compact, forming a pan. Internal drainage therefore decreases with increasing soil depth. The major difference between the hill and steepland soils is that the steepland soils are shallower and slightly less compacted. The Shannon soils also contain gravel in the subsoils, which are also compact.

Prior to planting soil testing was carried out separately for each microsite (Table 3.1). Soil cores (15 cm) were randomly taken from 20 positions, bulked and submitted to the Fertiliser and Lime Research Centre, Massey University for analysis of pH, macronutrients, organic matter and cation exchange capacity.

A notable feature of Table 3.1 is the relatively high P content, indicating that high rates of phosphate have been applied in the past (Pollock & McLaughlin 1986). The cation exchange capacity and exchangeable cations levels are similar to the values reported by Cowie (1978) for these soil types. Cation exchange capacity is moderately low indicating low clay content in the top soil.

Table 3.1 Soil nutrient analysis for each microsite. Phosphate (P), sulfate (S), potassium (K), calcium (Ca) and magnesium (Mg) are expressed in µg/g of soil (air dry) (Cornforth & Sinclair 1984). Sodium (Na) and cation exchange capacity (CEC) are expressed in meq/100g of soil (air dry). Organic matter (C) was determined by loss on ignition (550°C) and expressed as % of an oven-dried sample.

	pH	P	K	S	Ca	Mg	Na	CEC	C
Upper sun	5.3	34	0.48	8.3	3.2	2.35	0.4	15	5.4
Lower sun	5.5	41	0.49	17.8	4.7	2.24	0.2	15	7.0
Upper shade	5.3	45	0.60	11.6	4.0	1.79	0.3	19	8.2
Lower shade	5.5	29	0.39	15.0	3.1	1.95	0.3	14	5.8

3.2.3 Climate

Tuapaka is located near the eastern boundary of the Manawatu region, running from the top of the Tararua range, which at its northern end reaches to about 500 m in altitude, westwards to the Tasman sea. Burgess (1988) has described the Manawatu climate in detail. A brief summary is provided here. Categorised as cool temperate, summers are warm and winters mild with an annual average temperature at Palmerston North, the main population centre, of 12.9°C (New Zealand Meteorological Service 1983). Rainfall varies from a little under 900 mm on the coast to over 2500 mm at the top of the Tararua range. The trial site lies between the 1020 and 1140 mm isohytes. There is a similar coast - inland gradient in sunshine hours (solar radiation), sunshine declining from over 2000 hours/annum on the coast to less than 1800 hours at the foot of the ranges and considerably less than this in the ranges. A feature of the Manawatu region is high wind run, predominately from the west and northwest which may reach gale force four to five times a year. The Tararua's intersect these winds, resulting in wind speeds accelerating as they pass over the ranges. Mean daily wind speed across the northern Tararua range is 44 km/hr, sufficient to allow electricity generation from wind power, whereas at Palmerston North (10 km to the west) mean daily wind speed is 15 km/hr. The trial site is exposed to the prevailing winds. Chapter four presents detailed climatological information collected from the trial site.

3.2.4 Vegetation

The existing vegetation was primarily unimproved pasture containing mostly grass species tolerant of low fertility, including browntop (*Agrostis capillaris*), sweet vernal (*Anthoxanthum odoratum*), perennial ryegrass (*Lolium perenne*), Yorkshire fog (*Holcus lanatus*), crested dogstail (*Cynosurus cristatus*) and on the sunny face paspalum (*Paspalum dilatatum*) as well as legumes including lotus major (*Lotus pedunculatus*), white clover (*Trifolium repens*), subterranean clover (*Trifolium subterranean*) and suckling clover (*Trifolium dubium*). Broadleaf species present included creeping buttercup (*Ranunculus repens*), catsear (*Hypochoeris radicata*), dandelion (*Traxacum officinale*), daisy (*Bellis perennis*) as well as Scotch (*Cirsium vulgare*) and Californian thistles (*Cirsium arvense*). A few gorse (*Ulex europaeus*) seedlings were also evident, particularly on the sunny face. The paddock had been sprayed with herbicide to control gorse in 1993.

3.3 *Eucalyptus* species

The list of species selected for evaluation (Table 3.2) includes some commonly planted species which perform well in most areas of New Zealand but which produce wood of limited value, for example *E. nitens*, and *E. regnans* (Haslett 1990; Hocking 1995), and serve as control species in this comparison. Other species have been selected because of their desirable wood properties, particularly the stringybarks, but which are generally less site tolerant and less productive (Nicholas 1991; Barr 1996). All but one species, *E. baxteri*, are recommended by Barr (1996), either as one of the ‘first eleven’ most proven species or as a potentially useful species for New Zealand conditions.

3.3.1 *Eucalyptus agglomerata*

Eucalyptus agglomerata, or blue leaved stringybark is a species which has not been widely planted in New Zealand (McWhannell 1960; Shelbourne et al 2003) despite the fact that the wood is hard and durable and is able to handle colder conditions than many other stringybarks (Boland et al 1984). This may be because it appears to offer few advantages over other favoured stringybarks such as *E. globoidea* and *E. muelleriana* (Hathaway & King 1986; Bulloch 1991; Barr 1996).

3.3.2 *Eucalyptus baxteri*

There is very little information available on the performance of this species in New Zealand. The New Zealand Forest Research Institute has begun to measure some permanent sample plots of a number of stringybark species including *E. baxteri* (Shelbourne et al 2003). It is a *Monocalyptus* species from the stringybark group with desirable wood characteristics and is likely to tolerate environmental conditions in the southern North Island (Boland et al 1984).

3.3.3 *Eucalyptus botryoides*

Common name is southern mahogany because of the similarity of the heartwood to Honduran mahogany (McWhannell 1960). The heartwood is red when dry and has been used extensively for furniture but it is also reasonably durable (Boland et al 1984; Barr 1996) allowing its use for purposes such as decking. However *E. botryoides* often suffers from tension wood or growth stress which causes brittleheart and distortion, reducing recovery of sawn timber during milling (Haslett 1990). It has been widely planted in New Zealand and has performed well in moist, sheltered sites (Barr 1996), where it is capable of rapid growth (Hathaway & King 1986; Bulloch 1991), and it is tolerant of salt winds (Wilcox 1997). Latterly, however' it has suffered from the arrival of several insect pests from Australia which have reduced the vigour of many stands. These include *Ophelimus eucalypti*, first discovered in Wellington in 1985 and which produces leaf galls on the new growth of Eastern blue gums (Maclaren 1989), *Cardiaspina fiscella*, a lerp-forming psyllid, first discovered in 1996 near Auckland airport (Treeby 1997a) and *Uraba lugens*, a leaf skeletoniser, first found at Mt Maunganui in1997 (Treeby 1997b).

3.3.4 *Eucalyptus cladocalyx*

This species has relatively palatable foliage when young, due to high concentrations of glucosides, resulting in the common name of sugar gum (Boland et al 1984). It is the only endemic South Australian species in the study (Table 3.2). Though not a member of the stringybarks, it possesses many of the desirable wood characteristics found in this group. It is very heavy, hard and durable (McWhannell 1960; Barr; 1996), for example, density at 12% moisture content is around 1100 kg/m^3 (Boland et al 1984). It is planted extensively in Victoria for farm timber and shelter (Burke 1998). Reputed to be able to handle a wide range of soils and moisture conditions, performance is only good on better sites (McWhannell 1960). Hathaway and King (1986) found that *E. cladocalyx* was one of the best species at the better of two sites in the Wairarapa. However, a problem noted by some growers and researchers in New Zealand is poor form (Bulloch 1991; Barr 1996; Shelbourne et al 2002).

3.3.5 *Eucalyptus globoidea*

One of the more common stringybarks in Australia, the wood of *E. globoidea* is lighter in colour than many other species of this group, hence its common name of white stringybark (Boland et al 1984). Widely planted in New Zealand, particularly in the Bay of Plenty where it was included in some local harbour board plantations (Barr 1996). A small stand was established on Matakana Island, Tauranga harbour, some trees of which have been sawn and evaluated for yield, sawn timber grade recovery and wood density (Somerville & Gatenby 1996). Although a small study, it is one of the few on milling of stringybarks in New Zealand. *E. globoidea* appears to offer few advantages over other stringybark species, such as *E. muelleriana,* in New Zealand (Shelbourne et al 2002), particularly on less productive sites (Bulloch 1991). It is not suited to sites with poor drainage (Barr 1980).

3.3.6 *Eucalyptus microcorys*

The natural range of *E. microcorys* extends no further south than 33° (Table 3.2), well to the north of the northern most point of the North Island (approximately 35° south), suggesting that it may not be well suited to the Tuapaka site. The wood has a greasy feel to it, even when dry, explaining the common name of tallowwood (McWhannell 1960). Known for its exceptional durability making it suitable for heavy engineering applications such as railway sleepers and poles (Boland et al 1984), it is not a particularly fast growing species (Cotterill et al 1985; Hocking 1995) but appears to be suited to many upper North Island sites, except the Volcanic Plateau (McWhannell 1960), and lower North Island sites free of hard frosts (Hocking 1995).

3.3.7 *Eucalyptus muelleriana*

This is probably the most promising of the stringybark species, possessing the desirable wood characteristics of this group (Forest Research Institute 1984), being relatively easy to mill (Haslett 1990) and one of the better adapted and more productive stringybark species (Hocking 1995; Shelbourne et al 2002). However, it is noted for its forking tendency, resulting in multiple leaders (Shelbourne et al 2000b). The heartwood is a creamy yellow colour giving it the common name of yellow stringybark (Boland et al 1984). It has been planted for quite some time in warmer areas of New Zealand, mostly the North Island (McWhannell 1960) with good results. Many of the early planted stands in Northland are now being milled, fulfilling the promise of good recovery and high quality timber from this species (Davies-Colley 1995). This is the only stringybark species for which information on the performance of different provenances in New Zealand has been published. There appears to be negligible provenance effect on early growth (6 years), however, provenance does appear to have a small influence on tree form, the best provenances coming from Mount Kembla, NSW and also Eastern Victoria (Shelbourne et al 2000b).

2.3.8 *Eucalyptus nitens*

Eucalyptus nitens is probably the most widely planted *Eucalyptus* species in new Zealand (Barr 1996). Thousands of hectares have been planted on the Volcanic Plateau to help satisfy the local demand for hardwood pulp and a significant plantation exists in Southland, destined to provide hardwood chips for export (Neilson & Buckleigh 2002). It is commonly planted on farms throughout New Zealand for shelter and firewood (Barr 1996). It is a very productive species adapted to a wide range of environments (Wilcox et al 1985; Bulloch 1991), including sites which are exposed and which experience hard frosts (Johnson & Wilcox 1989), as low as -14°C (Forest Research Institute 1984). However, performance has been disappointing in Northland where warm temperatures and moisture stress result in poor canopy health (Shelbourne et al 2000a) and consequently high mortality, particularly for Victorian provenances (Low & Shelbourne 1999). It also generally has very good form (Shelbourne et al 2002). This is an example of a species which has benefited greatly from the introduction of a biological agent in the late 1980's, *Enoggera nassaui* (Forest Research Institute 1990), a wasp which parasitises the eggs of *Eucalyptus* tortoise beetle (*Paropsis charybdis*), the larvae of which severely defoliated several species from the southern blue gum group including *E. nitens*, particularly the mature foliage (Bain 1977; Forest Research Institute 1984; Johnson

& Wilcox 1989). There has been some research to identify provenances suitable for New Zealand conditions. Most of the central Victorian provenances perform better than those from southern New South Wales and northern New South Wales but similarly to the eastern Victorian provenances (Wilcox et al 1985; King & Wilcox 1988; Bulloch 1991). The seed used in the current study comes from trees at the Waiouru Army Base of eastern Victorian origin, probably Mount Saint Gwinear, which has performed well in New Zealand (Miller et al 1992). Although suitable for pulp the wood of *E. nitens* is not particularly attractive, easy to mill, or durable (Haslett 1988b). Its common name is shining gum after the glossy appearance of adult leaves (Boland et al 1984).

3.3.9 *Eucalyptus obliqua*

One of the ash species, its common name may be Tasmanian oak, because of the similarity of the wood to European oak (Barr 1980), or messmate stringybark, due to the fibrous nature of the bark. It is one of the most widely distributed (> 15^{O} of latitude, Table 3.2) of the south eastern eucalypt species (Boland et al 1984). The best trees however are found in hilly areas of Tasmania (Barr 1996). It is one of the better performing eucalypt species in New Zealand though generally not as productive as other ashes, particularly *E. regnans* (Wilcox 1979; Wilcox et al 1985; Johnson & Wilcox 1989; Bulloch 1991). It is also more frost sensitive than other ash species, for example *E. regnans*, *E. delegatensis* and *E. fastigata* (Wilcox et al 1985; Johnson & Wilcox 1989). It has been widely planted in New Zealand and many stands have been milled but with mixed results. Typical problems have included checking and distortion due to tension wood (Haslett 1988b). It has been utilised for furniture and veneer.

3.3.10 *Eucalyptus pilularis*

Though often referred to as a stringybark and closely related to the stringybarks *E. pilularis* is botanically distinct from the stringybarks, belonging to a small group of species named the blackbutts (Boland et al 1984). Blackbutt (common name) refers to the appearance of the lower trunk after fire. It does posses the desirable wood characteristics of the stringybarks however and is often included in this group based on this fact (Haslett 1990; Barr 1996). It is one of the most important commercial species in Australia. It was used in situations where strength and durability were crucial, including railway sleepers, poles and posts. A lot of the timber was imported into New Zealand for these purposes. Most plantings to date have been in Northland probably because it is a frost sensitive species and regarded as too risky further south (McWhannell 1960; Barr 1996). However it is being successfully grown in the coastal Bay of Plenty (Davies-Colley 1998) and the Rangitikei (Hocking 1995) on north facing slopes. There is little published information on the performance of *E. pilularis* in New Zealand though experience in Northland shows that it grows well on a wide range of soil types (Barr 1996) and may be just as productive as the ashes in that region (Shelbourne et al 2003). It is regarded as one of the best milling species in New Zealand (Barr 1996) because of its freedom from tension wood and good seasoning characteristics (Haslett 1990). The most widely utilised seed source was from a stand originally planted in the Waipoua Forest, Northland (Barr 1996). This seed is no longer available but trials have been established (Bay of Plenty and Northland) to identify suitable provenances. However the trees are too young to allow any firm conclusions to be made (Davies-Colley 1998).

2.3.11 *Eucalyptus regnans*

Trees of this species achieve heights greater than any other hardwood species: On good sites reaching 100m or more (Boland et al 1984). It is one of the ash group found naturally in the high country of Tasmania and Victoria (Table 3.2), giving rise to its common name of mountain ash (Barr 1996). It is a major timber species in

Australia utilised for a range of end uses including furniture, flooring and pulp (Boland 1984). It has been planted extensively in New Zealand (McWhannell 1960) and is one of the more productive species in cooler regions (Wilcox 1985; Johnson & Wilcox 1989; Bulloch 1991). However, it is a site sensitive species intolerant of low fertility and hot dry conditions (Barr 1996), and is also unsuitable for sites which suffer severe frosts (Johnson & Wilcox 1989). Temperatures below about - 10°C may result in high mortality (Forest Research Institute 1984), though there is provenance variation for this with high altitude provenances displaying more resistance to frost than low altitude provenances (Wilcox 1982). The largest resource in New Zealand is located on the Volcanic Plateau and utilised for hardwood pulp production (Wilcox 1979; Ministry of Agriculture and Forestry 2002). As with many of the ash species *E. regnans* often suffers from tension wood and brittle heart, resulting in distortion of sawn timber and poor conversion rates (Haslett 1988b).

3.3.12 *Eucalyptus saligna*

An eastern blue gum closely related to *E. botryoides*, a species it readily hybridises with (Boland et al 1984). It is quite common along the New South Wales coast, particularly from Sydney north giving rise to the common name of Sydney blue gum. It has pink heartwood making it suitable for furniture but it has reasonably good natural durability allowing its use in outdoor situations, such as decking, which don't involve ground contact (McKenzie & Hay 1996). However, it tends to suffer from high levels of growth stress (Haslett 1990; McKenzie & Hay 1996). It has been widely planted in the warmer areas of New Zealand (McWhannell 1960; Barr 1996) but interest is waning because of the arrival of insect pests from Australia which have targeted *E. saligna* (and *E. botryoides*, Section 3.2.3) and because growth in mature trees has been disappointing, possibly because of insect defoliation (McKenzie & Hay 1996). It will not tolerate hard frosts and is also vulnerable to wind damage which results in broken tops and branches (Forest Research Institute 1984). On moist sheltered sites it has grown to large size. A provenance originating from southern

New South Wales growing on the Bartlett property at Silverdale north of Auckland has been widely planted because of its good milling properties (Barr 1996).

3.4 Seedling propagation

Seed was sourced from Proseed New Zealand and from the Australian Tree Seed Centre, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia (Table 3.3). Provenances of species purchased from Proseed were selected from both New Zealand and Australian sources, based on experience of performance in New Zealand conditions (Proseed 1994). Provenances of species obtained from the CSIRO were selected according to the assessed suitability to trial site conditions as well as knowledge of performance in New Zealand (Craig Gardiner, Australian Tree Seed Centre, personal communication).

Seed of *E. muelleriana* (4 weeks), *E. nitens*, *E. obliqua* and *E. regnans* (3 weeks) was stratified at 5°C prior to sowing. On 2/5 1995 seed of all species was sown onto trays filled with sand, placed in a glasshouse and watered daily. Seed of different species germinated at different times, the first to emerge being the ash species, six days after sowing, the slowest being *E. cladocalyx* 16 days after sowing. Seedlings were pricked out into Hilson® root trainers (172 ml capacity) using potting mix (five parts peat, two parts pumice, two parts bark and 400 g/m^3 of slow release fertiliser, 3-4 month Osmocote®, N P K = 15 : 5.2 : 12.5). Pricking out was done at the cotyledon stage, *E. regnans*, *E. obliqua* and *E. botryoides* on 8/5, *E. saligna* on 9/5, *E. muelleriana* on 10/5, *E. nitens* on 11/5, *E. agglomerata* and *E. microcorys* on 12/5, *E. globoidea* and *E. pilularis* on 14/5, *E baxteri* on 15/5 and *E. cladocalyx* on 18/5. Germination appeared to be good in all species except *E. cladocalyx*. Seedlings were held in a glasshouse and watered daily. Benomyl (500 g/kg) fungicide was applied on 24/5 to control damping off and subsequently on 18/7 to control grey mould (*Botrytis cineria*) which was affecting seedlings from all species, but *E. cladocalyx* in particular. Seedlings were removed from the glasshouse in early September 1995, once the danger of hard frosts had passed, to harden off prior to planting.

Table 3.2 Species natural distribution and environmental range (Boland et al 1984)

	Monocalyptus						
	Stringybarks				Blackbutts	Ashes	
	E. agglomerata	E. baxteri	E. globoidea	E. muelleriana	E. pilularis	E. obliqua	E. regnans
State	NSW	VIC-SA	VIC-NSW	VIC-NSW	NSW-SQ	TAS-SA-VIC-NSW	TAS-VIC
Latitude (°S)	32-37.5	34-39	30-38	32.5-39	24-32	28-43.5	37-43
Altitude (m)	0-1000	0-1000	0-1100	0-450	0-600	0-1200	150-1100
Mean min temp.(°C)	-2 to 6	2 to 8	1to 6	1 to 6	5 to 10	-4 to 8	-2 to 4
Frosts* (no./yr)	0-80	0-20	0-40	0-20	0-few	0-100	few-80
Rainfall (mm/yr)	700-1150	500-1100	1000-2000	7009-1200	900-1750	500-2400	750-1700

	Symphyomyrtus				Nothocalyptus
	Eastern blue gums		Southern blue gums	Mallees	
	E. botryoides	E. saligna	E. nitens	E. cladocalyx	E. microcorys
State	VIC-NSW	NSW-SQ	VIC-NSW	SA	NNSW-SQ
Latitude (°South)	32.5-38	21-36	30.5-38	32.5-36	25-33
Altitude (m)	0-300	0-1100	1000-1300	0-600	0-750
Mean min. temp.# (°C)	2 to 8	-2 to 8	-5 to 2	4 to 9	0 to 10
Frosts* (no./yr)	few-20	0-60	50-150	0-20	0-60
Rainfall (mm/yr)	700-1300	900-1800	750-1750	380-650	1000-2000

* min air temperature ≤ 2.0°C

\# Mean minimum temperature of the coldest month

3.5 Planting

Three weeks prior to planting the area to be planted was fenced off using three wire electric fences. Planting spots were marked and spot sprayed with a herbicide mixture and applied at a rate of 6 l/ha of glyphosate (360 g/l), 2 l/ha of clopyralid (300 g/l) and 2 l/ha of simazine (500 g/l), using a hand operated spot gun applying 20 ml of herbicide mix at each spot. A pre emergence herbicide application was used because of the sensitivity of some eucalypts to the commonly used post emergence residual herbicides such as terbuthylazine and terbumeton (Hathaway & Sheppard 1986). The weed control spectrums of glyphosate and clopyralid allowed good control of all grass and broadleaf species present in the sward. The inclusion of simazine, which controls weeds by killing germinating seedlings, allowed residual control of many grass and broadleaf species. Simazine may damage seedlings of some tree species if it comes into contact with the roots, consequently care was taken during planting not to allow surface soil to fall into the planting hole.

Seedlings were planted by hand, using spades, from October 6 to October 10 1995. Each species was represented on each microsite by seven tree plots, replicated three times and orientated perpendicular to the contour. Plots on the upper slope were separated from those on the lower slope by 12 m. The bottom of the plots on the lower slope were situated approximately 5 m from the stream bed in order to avoid seepages. All replicates on each microsite were individually randomised. Each species was represented by 21 seedlings (three plots) on each microsite and 84 seedlings in total. Seedlings were approximately 3 m (slope distance) apart within a plot with 4 m between plots. The distance between the centres of planting spots was not adjusted for slope, consequently, horizontal distance between spots was approximately 2.8 m. In practice spacing between seedlings varied because the exact positioning of seedlings in each spot was determined by local factors, for example, the presence of rocks, stumps, banks and stock tracks.

Table 3.3 Supplier and origin of seed for each species.

	Supplier	Seedlot No.	Locality
E. agglomerata	CSIRO	15284	32.3 km N Batemans Bay, NSW
E. baxteri	CSIRO	15995	20.3 km NNW Lakes Ent., VIC
E. botryoides	Proseed NZ	94/258	Orbost, VIC
E. cladocalyx	CSIRO	16013	6.7 km NE Wirrabara Fo., SA
E. globoidea	Proseed NZ	93/149	Goonerah, VIC
E. microcorys	Proseed NZ	94/230	Kendall, NSW
E. muelleriana	Proseed NZ	93/378	NSW
E. nitens	Proseed NZ	94/13	Waiouru, NZ
E. obliqua	Proseed NZ	88/91	TAS
E. pilularis	Proseed NZ	1/0/79/113	Waipoua, NZ
E. regnans	Proseed NZ	94/224	VIC
E. saligna	Proseed NZ	94/346	NSW

3.6 Post planting management

Immediately after planting surplus seedlings (21 of each species) were transferred into PB 8 polythene planter bags (capacity 5 litres) using potting mix consisting of finely granulated *P. radiata* bark with 3 kg/m^3 of slow release fertiliser (8-9 month Osmocote® N P K = 16 : 3.5 : 10). Initially, weekly monitoring of seedlings was carried out to ensure any potential problems were well managed. Possum browsing damage became evident in mid November and consequently poison bait was used to control possum numbers. Details are provided in Chapter Five.

The trial was blanked in March 1996, using the surplus planting stock. Figure 3.2 shows a typical example. Spiralling of roots was apparent in some of the replacement trees, consequently, the outer root ball of each was cut (vertically) in each quarter immediately prior to planting to prevent root strangulation. The position of every blanked tree was recorded. In late March 1996, 60 g of urea (46% nitrogen) was applied into a spade slit cut approximately 30 cm from the base of each tree on the contour (Hathaway 1986). Young eucalypts respond well to nitrogen (N) fertiliser on many sites in New Zealand and application in the first six months after planting is normal practice (Knight & Nicholas 1996). There was a marked visual response to this treatment; the foliage of most trees changing from pale to dark green within a few weeks of application and tree vigour was good during the autumn of 1996.

During the first winter (June to August 1996) the trial was monitored for signs of frost damage. While a few frosts were recorded (Chapter 4), evidence of frost damage, even in the most sensitive species, was absent. No evidence of frost damage was noted in subsequent winters.

3.7 Rainfall, temperature, solar radiation and exposure.

The nearest comprehensive meteorological station to the trial site is located at the New Zealand Institute for Agricultural and Pastoral Research (AgResearch), Palmerston North (Station E05363), about 10 km distance. Temperature and rainfall data collected at the trial site are compared with data collected from this station when appropriate. There is also a meteorological station (Ballantrae) located just north of the Manawatu Gorge on the eastern flank of the southern Ruahine Range, also at about 10 km distance. However, only rainfall and wind records are available at this site.

3.7.1 Rainfall

Rainfall (monthly) was recorded from November 1995 using a standard 250 mm gauge situated in the gully bottom near the western edge of the trial. Rainfall was recorded several times during each month and always on the morning of the 1st of each month to ensure monthly totals could be accurately determined. Cattle broke into the trial on several occasions during the summer and autumn of 1997 and damaged some equipment, including the rain gauge. Consequently recording of rainfall stopped in March 1997.

3.7.2 Temperature and solar radiation

Daily maximum, minimum and average temperature and total daily solar radiation were recorded with Omnidata DP219 datapods (Omnidata 1984), a battery powered field data logger, situated on both aspects and in the gully bottom. Temperature was measured with an Omnidata TP10V temperature probe and solar radiation with a LiCor Li200S pyranometer. Temperature and solar radiation were recorded in degrees Fahrenheit and Langleys respectively, at 10 minute intervals, and converted to ^{0}C and MJ/m^2/day after downloading (New Zealand Meteorological Service 1983). Up to nine months of data can be stored in each pod. The datapods and temperature probes were housed in Stevenson screens (double louvred) 1 m above the ground and the pyranometers were set (level) on a post just uphill and above the screens. The screens were located between the lower and upper microsites on each aspect, and in the gully bottom, at about the middle of the trial site. Recording began on 1/6 1996 and continued for 36 months. Cattle damage resulted in the loss of the datapod and stored data located in the gully bottom in January 1998. The datapod on the sunny face suffered a terminal malfunction sometime in late 1998. Recording at the remaining location (shady face) ended in July 1999.

3.7.3 Exposure

Wind has a major impact on the performance of many tree species. It causes trees to topple resulting in death or stem sweep in survivors (Mason 1985), breakage of leaders and branches (Maclaren et al 1995), increased evapotranspiration, dessication and reduced photosynthesis and growth, particularly height (Telewski 1995). Wind speeds are generally highest on exposed sites (Burgess 1988). The topographic exposure at the trial site was measured by use of the TOPEX index (Wilson 1984). The index is usually calculated by measuring the inclination (degrees) to the horizon at the eight main points of the compass, (N, NE, E, SE, S, SW, W & NW) and totalling these. High values indicate a relatively sheltered site while low values indicate an exposed site.

In addition to TOPEX, windiness was assessed at 12 locations across the trial site using tatter flags. Tatter flags (Figure 3.2) are normally constructed from madapollam cloth, a type of callico, measuring 380 mm long by 305 mm wide. The wear rate (tatter) is influenced by windiness, being faster in windy conditions (Quine & White 1994). Madapollam cloth was not available so a standard callico cloth was used instead. Flags were attached to the flag mount by holders constructed of stainless steel and the mounts were held upright by stapling to wooden battens (50 x 50 mm) driven into the ground. Twelve tatter flags were monitored. Three flags were placed on the mid slope area (between the upper and lower slope positions), three flags in the gully bottom, three flags in the mid slope area on the sunny face and three flags just above the upper slope position on the sunny face. Flags were set up on the 1st of July 1998 and replaced every 60 days, the position of each flag and period of exposure being recorded. The TOPEX of each flag site was also measured. Monitoring continued until January 2000. After removing and trimming of loose threads, the mid point length of each tattered flag was measured and the area of each flag was measured with a leaf area meter. The length of tattered flags has been used as a reliable means of estimating the area of flag loss in overseas work and the validity of this was evaluated (Reynard & Low 1984). The relationship between the mean rate of flag loss was investigated using non linear regression.

3.8 Tree assessments

3.8.1 Diameter and height

Measurement of height and DBH began in late August 1997 and continued on a seasonal basis for two years, concluding in August 1999. Winter; June to August, spring; September to November, summer; December to February, autumn; March to May. Trees were also measured in August 2000 at 5 years of age. Diameters were measured with a standard Richter fibreglass diameter tape (2.0m length) at a height of 1.4m, measured from the uphill side of the tree. Initially the height of all trees was measured with a fibreglass height pole (Hastings height pole, model number 2131). For the final assessment a trigonometric approach was taken because the taller trees were beyond the maximum reach of the height pole (11.0 m). Slope distances were measured with a fibreglass tape and upper (top of tree) and lower angles (base of tree) were measured with a Suunto® clinometer. The techniques used for height and diameter measurement were based on those outlined by Dean (1989).

3.8.2 Tree form

In August 1999 each tree was visually assessed for stem form. Characteristics assessed included the number of stems, kink, wobble, lean, sweep, branch diameter and canopy balance. Canopy vigour and reproductive status were also assessed but not included in stem form. All characteristics were allocated a score of either 0, 1 or 2, with the exception of stem number which was allocated a score of 1, 2 or 3 (Table 3.4). Apart from stem number, a score of 0 means that the tree was free of defect, a score of 1 means that the tree had moderate defects while a score of 2 indicates that the tree had severe defects. For kink, wobble, lean and sweep, the criteria described by Maclaren (1993) were utilised to allocate scores. Lean of > 5° is not acceptable because it may result in sweep and will almost certainly result in tension wood (Forest Research Institute 1987). Kink, wobble and sweep acceptability scores are based on the deviation not resulting in the centre line of the tree (line running from the centre of the base to the growing tip) not passing outside the outer edges of the tree (Plate 3.2). If this should occur then the tree is unacceptable. Individual trees are categorised as unacceptable if they have more than one stem, achieve a score of 2 in any of the stem form traits or a score of 1 in more than one of the stem form traits.

Table 3.4 Allocation of visual scores of individual tree form.

	Score			
	0	1	2	3
Stem Number		1	2	>2
Stem Form				
Kink	None	Mild	Severe	
Wobble	None	Mild	Severe	
Lean	None	≤5°	> 5°	
Sweep	None	Mild	Severe	
Branches > 3cm diameter	None	1	>1	
Canopy Balance	Equilateral	Intermediate	Unilateral	

Plate 3.2 Examples of (left) unacceptable and (right) acceptable kink. Acceptability is based on the criteria in Table 3.4.

3.8.3 Foliar nutrients

The concentration of foliar nutrients in eucalypts is a reliable indicator of nutritional status in many species allowing the identification of critical levels and the probability of economic responses from application of fertiliser (Herbert 1996; Judd et al 1996b; Knight & Nicholas 1996; Barros & Novais 1996). Information on foliar nutrient concentrations can also indicate site quality and the adaptability of species to different sites (Judd et al 1996a). In March 1998 (2.5 years after planting) the foliage of all trees was sampled for determination of the concentration of nitrogen, phosphorus, potassium, magnesium and calcium. The timing of sampling in late summer is based on greater stability of nutrient concentrations at this time (New Zealand Forest Research Institute 1997a). Ten leaves from each tree were collected and bulked by plot. The most recent fully expanded leaves were collected from the upper canopy to avoid shaded and mature leaves which tend to exhibit high variation in nutrient concentrations (Forest Research Institute 1997b). After drying (85°C) samples were submitted to the Fertiliser and Lime Research Centre, Institute of Natural Resources, Massey University for analysis. Kjeldahl nitrogen and total phosphorus were determined by colorimetric auto-analysis methods (Technicon) following micro-kjeldahl digestion. Total calcium, magnesium and potassium were determined by atomic absorption/emission spectroscopy following digestion in nitric acid (Lance Currie, Institute of Natural Resources, Massey University, personal communication).

3.8.4 Basic wood density

In September 1999 two trees in each plot were randomly sampled for estimation of wood density. However, trees with serious defects such as severe sweep or excessive lean were avoided to minimise the risk of reaction wood being included in samples. The structure of reaction wood may be different from normal wood and even though this typically has a minimal effect on wood density in angiosperms (Clifton 1990), trees likely to contain reaction wood were avoided as a precaution. Sample cores were taken using a Haglöf 200 × 5 mm increment borer (up to 200 mm length). The borer was wound into the centre of each stem to be sampled, after measuring DBH, on the eastern side. After extraction cores were placed into sealed, labelled plastic bags to prevent any loss of moisture. Cores were processed by dividing into two equal segments (inner and outer) and the ends squared. The length of each segment was measured with a vernier caliper and weighed on a Metler AE100 electronic balance (accurate to 0.0001g). After weighing cores were placed in labelled paper bags and dried in a forced air oven at 85°C for 48 hours. No further weight loss could be detected in samples dried under this regime. Basic wood density was calculated by dividing the dry weight (g) by the green volume (cm^3) of each segment and converted to kg/m^3 (Harris et al 1995).

Two *Eucalyptus* species trials established in the Wairarapa region in 1979 to assess suitability for slope stabilisation (Hathaway & King 1986) included a number of species used in this study. Different provenances of several species were also included in these trials. One trial is located at Pakaraka, 8 km south of Masterton and the other at Kahuiti, 28 km east of Masterton. Both are hill country sites with a northerly aspect and at a similar altitude to the Tuapaka site. These trials were sampled for basic wood density but confined to common species. The objective was to examine the feasibility of using wood density from young trees (Tuapaka) to predict density of older trees of the same species but on different sites. Species sampled were *E. agglomerata*, *E botryoides*, *E. cladocalyx*, *E. globoidea*, *E. muelleriana*, *E. nitens*, *E. obliqua* and *E. regnans*. At Kahuiti good survival, clear labelling (aluminium tags) and the high retention rate of wooden battens used to attach tags meant that species, provenance and replicate were able to be identified. Two provenances of *E. nitens* and *E. regnans* were sampled. Sampling involved randomly selecting two trees from up to four replicates of each species and provenance. Four replicates of *E. botryoides*, *E. nitens*, *E. obliqua* and *E. regnans* were sampled, three replicates of *E. agglomerata* and two replicates of *E. cladocalyx*, *E. globoidea* and *E. muelleriana*. At Pakaraka heavy thinning and missing tags meant that *E. agglomerata*, *E. cladocalyx* and *E. muelleriana* were either no longer represented or unable to be located, meaning only five species were sampled. Also provenance was not able to be identified with any confidence and replicates of most species were missing. Consequently sampling was limited to 3-5 trees of each species. Both trials were sampled in May 2003 when the trees were 24 years of age. DBH of all sampled trees was also measured. Means and standard errors were calculated for individual species and provenances (Kahuiti) at both sites.

3.8.5 Root morphology

The morphology of tree roots influences stability under both wind stress and static loading due to gravity, particularly on hill sites and where the tree is not vertical or where the canopy is not balanced (Telewski 1995). Wind can also influence root development (Stokes et al 1995). The roots of six trees, one from each replicate on the bottom sunny and shady aspects, of a wind tolerant species, *E. nitens* (Nicholas 1991) and an intolerant species, *E. saligna* (Barr 1996) were excavated by hand (spade and chainsaw), to a distance of approximately 80 cm on all sides, in December 2002. The root ball of each tree was identified and marked to allow orientation with respect to slope to be determined in the laboratory. The diameter of the stem at ground level was measured on each tree prior to removal. The number and diameter of all roots greater than 5mm in diameter at a point 10 cm from its junction on the bole and Menzies' lateral root score (Mason 1985), which measures the radial distribution of roots around the root ball, were recorded after removal. Scores were based on the number of roots in quadrants around the stem. The presence of strong lateral roots in all quadrants results in a low score, while the absence of lateral roots results in a high score (Table 3.5). The number of lateral roots in the uphill and windward quadrants were determined and differences between species and aspects analysed (ANOVA).

Table 3.5 Menzies' lateral root score.

Description of distribution of lateral roots	Score
All four quadrants	0
Three quadrants	2
Two adjacent quadrants	4
Two opposite quadrants	6
One quadrant	8
No significant laterals	10

3.9 Statistical analyses

Unless otherwise stated, all trees were measured at each assessment wherever possible. Plot means were calculated for each variable and used as the basis for various analyses. Whenever there is more than one observation per experimental unit there is a possibility of unequal subclass numbers. Subclass numbers did vary in this study due, for example, to tree deaths. A problem with unequal subclass numbers is that the plot means may have variance heterogeneity, contravening one of the assumptions underpinning the analysis of variance (ANOVA) and which impacts on the validity of statistical tests, for example the *F*-test (Steel & Torrie 1980). However in practice, even with quite unbalanced data, the use of plot means in an ANOVA utilising the randomised complete block design produces results comparable to more sophisticated analyses which weight plot means by their variances (Piepho 1997).

ANOVA was undertaken utilising the PROC GLM procedure in SAS (SAS 1989), with means calculated using the least squares option. The repeated measurement of the same trees from season to season and year to year is a problem because the response of an individual tree to treatments over time will include a contribution from the tree, consequently different observations over time will be correlated. Independent data is another key assumption of ANOVA (Steel & Torrie 1980). One way of bypassing this is to analyse data from different assessments over time separately, however this does not allow valid comparison of treatments over time. Another option is to analyse data from different times in a combined data set, allowing comparison over time. In SAS this can be achieved with the REPEATED option in PROC GLM (SAS 1989).

Analysis of covariance (ANACOV) was utilised as a means of controlling error in some situations (Steel & Torrie 1980). For example, the effect of possum browsing (Chapter 5) on the growth of trees can be removed allowing comparison of treatment means adjusted to remove the effects of possum browsing.

Relationships between variables are examined with the aid of scatter plots, linear correlation and linear regression. Where the relationship between variables is not linear, alternative appropriate analysis is used. In particular, the relationship between tree height and DBH for each species was described and analysed using the Petterson equation (Goulding 1995).

Non parametric analysis techniques were utilised where data have proven to be not normally distributed and where transformation has not resulted in normality. That data is normally distributed is another key assumption underlying the validity of the ANOVA (Steel & Torrie 1980). This problem arose with categorical data used to measure, for example the incidence of possum browse damage and seedling survival (Chapter 5). In this case Wilcoxon's test was used rather than ANOVA. The linear model used for the ANOVA is shown below.

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \lambda_l(\beta\gamma)_{jk} + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk} + \epsilon_{ijkl}$$

and, Y_{ijkl} = mean of the ith species on the jth aspect, kth position and lth block

μ = overall mean

α = Species effect, $_{i} = 1..12$

β = Aspect effect, $_{j} = 1..2$

γ = Position effect, $_{k} = 1..2$

λ = Block effect, $_{l} = 1..3$

It is similar to the model for a three factor factorial in a RCB design (Steel & Torrie 1980) except that blocks are nested within aspect and slope position.

All effects in the model are assumed to be random. Random effects are those which are drawn from a large population about which inferences are to be made (Wilk & Kempthorne 1954). In this case the *Eucalyptus* species were samples drawn from many potentially useful *Eucalyptus* species. In addition each species was represented here by just one provenance but for many species, provenance can significantly influence performance (Wilcox et al 1985; Bulloch 1991). The microsite factors of aspect and slope position vary tremendously according to factors such as altitude, orientation, soil type and slope angle.

Table 3.6 Mean squares for a three-factor factorial experiment, all factors random.

No.	Source	D F	Mean Square	*F* Ratio
9	Aspect	a-1	∈ + B(AP) + SAP + AP + SA + A	(9 + 2)/(4 + 7)
8	Position*	p-1	∈ + B(AP) + SAP + AP + SP + P	(8 + 2)/(3 + 7)
7	AP	(a-1)(p-1)	∈ + B(AP) + SAP + AP	(7 + 1)/(6 + 2)
6	Blocks(AP)	ap(r-1)	∈ + B(AP)	6/1
5	Species	s-1	∈ + SAP + SA + SP + S	(5 + 2)/(4+ 3)
4	SA	(s-1)(a-1)	∈ + SAP + SA	4/2
3	SP	(s-1)(p-1)	∈ + SAP + SP	3/2
2	SAP	(s-1)(a-1)(p-1)	∈ + SAP	2/1
1	Error		∈	

* Slope Position

Determination of appropriate *F* ratios required the utilisation of complex *F* tests (Steel & Torrie 1980). Complex *F* tests are required for the main effects of aspect, slope position and species as well as the aspect x slope position interaction (Table 3.6). For the species x aspect and species x slope position interactions, the species x aspect x slope position mean square is appropriate, and for the species x aspect x slope position interaction, the experimental error ($\in$) is appropriate. This presents a problem for calculation of the appropriate degrees of freedom. The estimation of the degrees of freedom for calculation of statistical significance requires that the degrees of freedom for each mean square in the F test numerator and denominator are weighted by its corresponding mean square (Satterthwaite 1946). Complex F tests and associated degrees of freedom were calculated with the aid of a Microsoft DOS based computer programme (Thwaite version 6.41) written by Dr I. Gordon, Institute of Molecular Biosciences, Massey University.

Orthogonal contrasts were used to test for differences between meaningful groups of treatments. For example, the means of species from the *Monocalyptus* and *Symphyomyrtus* subgenera are compared allowing conclusions to be made about differences in performance of species from different subgenera. Species groups within subgenera may also be compared, for example the stringybarks and the ashes, both of which are *Monocalyptus.*

The relationships between tree growth (height and DBH) foliar nutrient concentrations and environmental factors such as exposure and slope were explored using canonical correlation analysis. Canonical correlation is an extension of multiple regression, which involves multiple independent (X) variables and one dependent variable (Y), to include multiple X and Y variables (Afifi & Clark 1996). It is particularly appropriate when the dependent variables are moderately inter-correlated and therefore difficult to separate.

Chapter 4

Climate

4.1 Introduction

Climatic factors have a large influence on growth and productivity of eucalypts (Boland et al 1984) and are strongly influenced by hill country microsite, particularly temperature and radiation (Radcliffe & Lefever 1981). Accordingly, climatological information was collected at the trial site so that performance traits of different *Eucalyptus* species planted on different microsites could be analysed in relation to climatic factors. Collection of climatic data began in June 1996 and concluded in June 1999 for all variables except exposure, which concluded in January 2000. Data were collected from the shady aspect for the entire duration, but on the sunny face data were collected for the first two years only, and in the gully bottom for the first year only. While the intention was to collect data for three years at each location, failure of the recording equipment on the sunny face as well as stock (cattle) getting past the perimeter fence and causing damage to both the measuring and recording equipment in the gully bottom prevented this. Daily mean, maximum and minimum temperatures are presented by month in Appendices 1, 2 and 3. There are no long term climatic records for the site, however, long term records are available from meteorological station EO5363 located near Palmerston North (Lat. 40 23S Long. 175 37E), initially by the Grasslands Division of the Department of Scientific Research and latterly by the New Zealand Institute for Pastoral Research Ltd. (AgResearch), Palmerston North. This station is approximately 12 km from the trial site, altitude 34m. Long term climatic data for AgResearch is presented in Appendix 4 and climatic records for individual years from 1996/97 to 1998/99 are presented in Appendix 5.

4.2 Temperature

4.2.1 Mean temperature

Average daily temperatures at the trial site are compared with those recorded at AgResearch in Figure 4.1. Seasonal variations in mean temperature on the shady face were similar to those at AgResearch in all years. Correlations between mean daily temperature on the shady face and at AgResearch were strong and highly significant (P = 0.0001) in all years (r = 0.95, 0.96 and 0.95 for 1996/97, 1997/98 and 1998/99, respectively). However, temperatures were generally lower on the shady face with differences ranging from 0°C (September) to 1.1°C (November), 0°C (June and July) to 1.2°C (November) and -0.2°C (May) to 1.3°C (October) during 1996/97, 1997/98 and 1998/99, respectively. Notable features apparent in these figures include temperatures in May 1997 being warmer than for April (Figure 4.1a), an unusual occurrence (Burgess 1988). This was due to relatively cool weather in April and warm weather in May 1997 (Appendix 1). Temperatures in the early Spring of the 1996/97 season were also above average, for example the average monthly temperature for October 1996 was slightly higher than for November 1996, also atypical. In the 1998/99 season temperature in July 1998 was higher than June and August and at 11°C, well above the long term mean for AgResearch. The coldest month was usually July.

Seasonal mean daily temperatures for the shady face over the three year period June 1996 to May 1999 reveal typical seasonal variation patterns (Table 4.1). Mean temperatures in the summer were 7.9 to 8.8 °C higher than those in the winter. Mean annual temperature in 1997/98 was marginally warmer than 1996/97, but 1998/99 was considerably warmer than the previous two years, with warmer temperatures in all seasons.

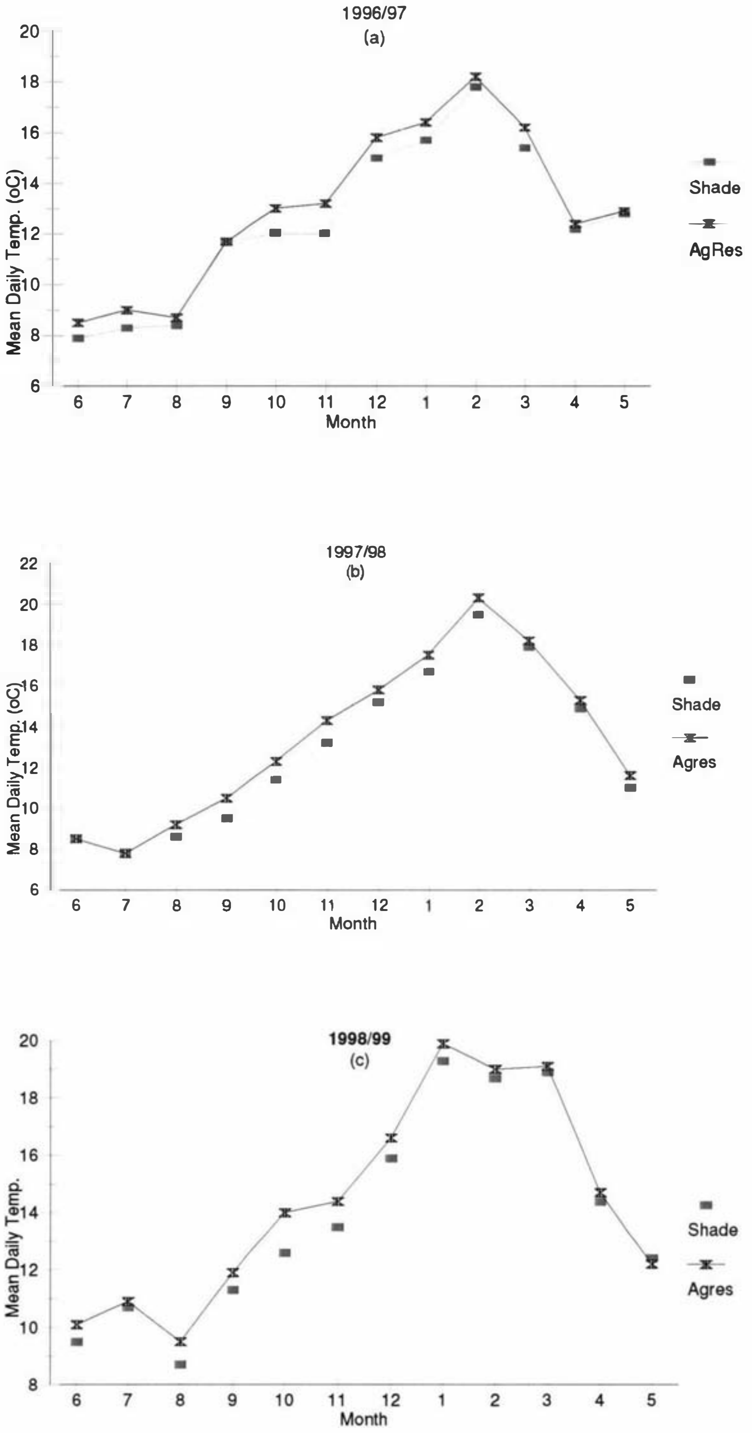


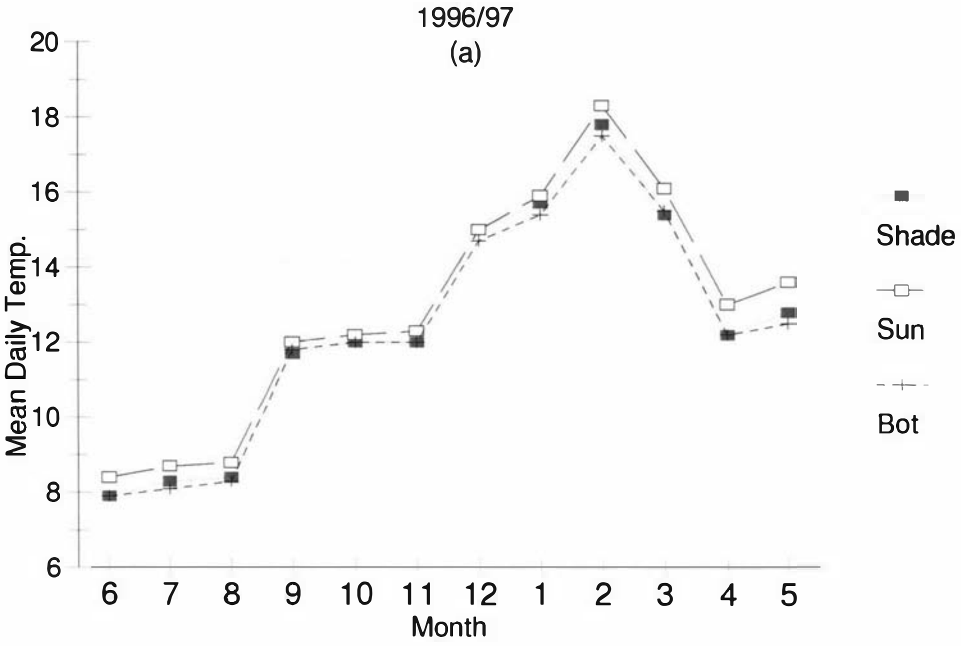
Figure 4.1 Mean daily temperature (°C) on the shady face compared with AgResearch, Palmerston North for the (a) June 1996 to May 1997, (b) June 1997 to May 1998 and (c) June 1998 to May 1999 periods.

Table 4.1 Seasonal and annual mean daily temperature (°C) for the shady face.

	Winter	Spring	Summer	Autumn	Annual
Year					
1996/97	8.2	11.9	16.1	13.5	12.4
1997/98	8.3	11.4	17.1	14.6	12.8
1998/99	9.6	12.4	17.9	15.2	13.8

A comparison of mean temperatures for each aspect (Figure 4.2) revealed that the shady aspect was generally cooler than the sunny aspect with differences being least during the summer months. This was a result of higher maximum temperatures on the sunny aspect (Appendix 1). Aspect differences in mean temperature for 1996/97 and 1997/98 are shown in Table 4.2. In 1996/97 mean daily temperature was significantly higher on the sunny face in all months except December, and in 1997/98, all months apart from December and January.

Mean daily temperature on the shady face was strongly correlated ($r = 0.99$) with mean daily temperature at AgResearch in all years ($P \leq 0.0001$). Similarly mean daily temperature for the sunny and shady aspects (Figure 4.2) were strongly correlated ($r = 0.99$) in both years as were the correlations between mean daily temperature for each aspect and gully bottom in 1996/97 ($P \leq 0.0001$).



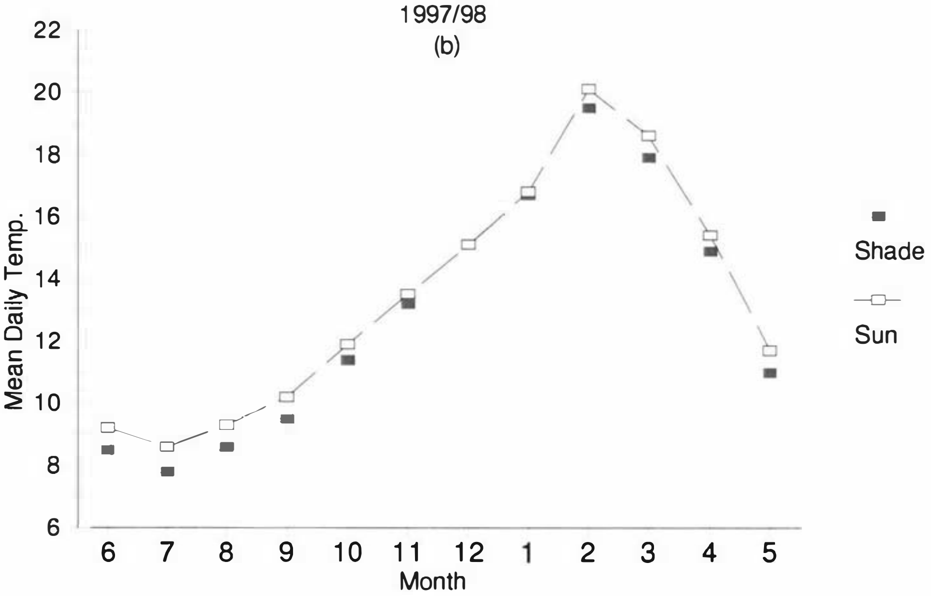


Figure 4.2 Mean daily temperature (°C) during (a) the 1996/97 year comparing aspect and gully bottom and (b) the 1997/98 year comparing aspect.

Table 4.2 Aspect differences (sunny-shady) in mean daily temperature (°C) during 1996/97 and 1997/98.

Month	1996/97	1997/98
June	0.42 **	0.73 **
July	0.45 **	0.84 **
August	0.41 **	0.62 **
September	0.33 **	0.66 **
October	0.23 **	0.46 **
November	0.23 **	0.26 *
December	0.03 NS	0.0 NS
January	0.2 *	0.08 NS
February	0.52 **	0.6 **
March	0.63 **	0.78 **
April	0.71 **	0.53 **
May	0.72 **	0.77 **

NS Not significant
* $P = 0.01$
** $P \geq 0.001$

4.2.2 Minimum temperature

Minimum temperature is an important environmental factor for many eucalypt species particularly those with low frost tolerance. In 1996/97 mean minimum temperatures were lowest in August with the shady and sunny aspect being similar at 4.8°C and 4.9°C, respectively, but minimum temperatures in the gully were significantly lower at 4.2°C ($P = 0.0001$) (Appendix 1). The following season mean minimum temperatures were lowest in July being 4.2°C and 4.0°C on the shady and sunny faces respectively (Appendix 2). Significant aspect differences in mean minimum temperature were the exception during 1996/97 and 1997/98, occurring in 5 of 24 months.

The extreme minimum temperatures recorded in each season occurred in the June to September period. Minimum temperatures on the sunny face were similar to those on the shady face but extreme minimum temperatures in the gully bottom were up to 1.1 °C cooler than on the slopes (data not shown). Table 4.3 reveals that over the three seasons only one air frost (-0.6 °C), defined as a minimum screen temperature of less than 0 °C (NZ Meteorological Service 1983), occurred on the shady face (4/ 8/ 98). In comparison the minimum temperature at AgResearch, Palmerston North on August 4th was -1.4 °C (Yvonne Gray, AgResearch, pers. comm.).

Table 4.3 Extreme minimum temperatures (°C) on the shady face.

Year	June	July	August	September
1996	0.0	0.6	0.0	2.2
1997	1.7	0.6	1.1	0.0
1998	1.1	1.1	-0.6	3.3

4.3 Global solar radiation

There was a strong seasonal effect on solar radiation (Figure 4.3). Solar radiation peaked in January with the exception of the sunny aspect during the 1997/98 season, which peaked in December. Lowest radiation levels were experienced during June and July in both years. The shady face received significantly less radiation than the sunny face except for the summer months where differences were small and in December 1996, radiation was actually higher on the shady face. In 1996/97 the gully bottom received more radiation than either aspect during the October to March period but was intermediate from April to September (Figure 4.3). The absolute differences in aspect radiation receipts were greater during the low radiation months and, combined with low absolute radiation during these months, resulted in relative differences being substantial. For example in June and July 1996 the sunny face received 42%, and 25% more daily radiation respectively than the shady face, and

45% more in May 1997. Differences were greater the following year, the sunny aspect receiving 60% and 63% more radiation than the shady aspect during June and July 1997 respectively and 51% more in May 1998. Conversely differences were generally less than 10% for the highest radiation months (November, December, January) in both years. Annual mean daily solar radiation on the sunny face was greater than the shady face in both years (Table 4.4) and, for both aspects, was lower than the long term estimated annual mean daily solar radiation at AgResearch. Solar radiation in the gully bottom was higher than both the sunny and shady faces between October and March during 1996/97. During the cooler months radiation in the gully was intermediate.

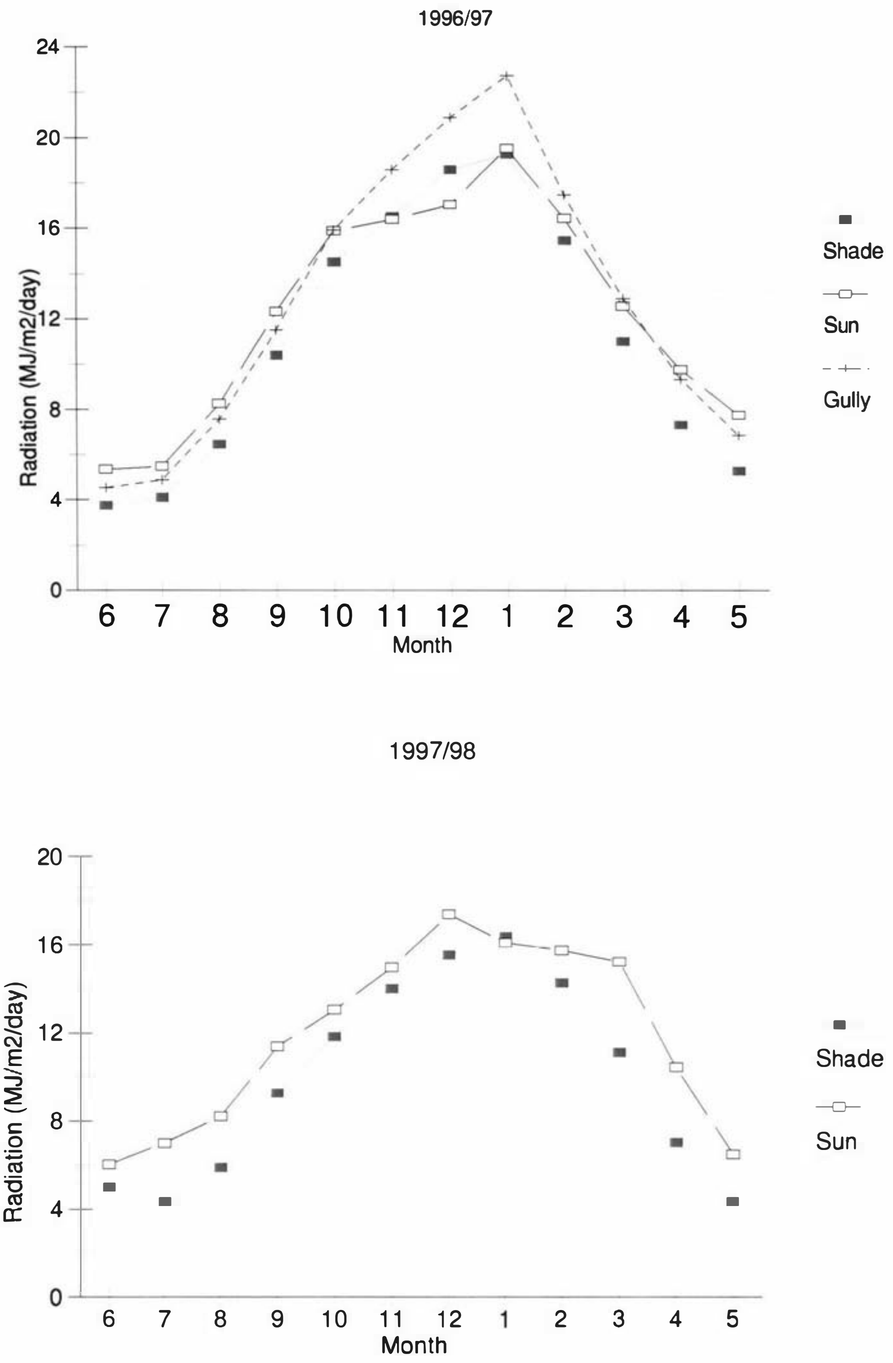


Figure 4.3 Mean daily global solar radiation (MJ/m²/day) for each aspect in (a) 1996/97 and (b) 1997/98.

Table 4.4 Mean daily global solar radiation (MJ/m^2/day) for the sunny and shady face. Estimated long term daily solar radiation for AgResearch is provided for comparison. Numbers in parentheses = SEM.

	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Annual
1996/97													
Sunny	5.4	5.5	8.3	12.3	15.9	16.4	17.0	19.5	16.4	12.5	9.8	7.7	12.2 (1.40)
Shady	3.8	4.1	6.5	10.4	14.5	16.5	18.6	19.3	15.4	11.0	7.3	5.3	11.1 (1.64)
1997/98													
Sunny	6.1	7.0	8.2	11.4	13.1	15.0	17.4	16.1	15.8	15.2	10.4	6.5	11.8 (1.19)
Shady	3.8	4.3	5.9	9.3	11.9	14.0	15.5	16.4	14.3	11.2	7.1	4.3	9.8 (1.34)
1998/99													
Shady	3.3	3.6	5.4	9.4	11.9	19.6	18.6	22.7	18.6	11.4	7.4	4.2	11.3 (2.0)
AgResearch*	5.7	6.3	9.1	12.7	16.5	20.2	22.0	22.3	20.3	15.7	11.0	7.5	14.1 (1.80)

*AgResearch solar radiation data are estimated from daily sunshine hours (Burgess 1988) using the equation of Coulter (1977).

4.4 Rainfall

Rainfall was recorded monthly from November 1995 to February 1997. Monthly totals at Tuapaka are listed alongside those recorded at AgResearch, Palmerston North for comparison (Table 4.3). Rainfall was evenly distributed and generally monthly totals at Tuapaka were similar to those recorded at AgResearch, an exception being September 1996 where rainfall at Tuapaka was only 55% that of AgResearch. Total rainfall during the first summer (November 1995 to March 1996) was 447 mm at Tuapaka and 461.7 at AgResearch which was close to the long term mean. Total rainfall in 1996 was 1146.5 mm and 1208.9 mm at Tuapaka and AgResearch respectively, the latter being 22% above the long term mean (Table 4.5). The Tuapaka and AgResearch sites both fall into a narrow band, typically receiving between 1000 and 1200 mm, lying between the Manawatu Plains and the northern Tararua Range (Burgess 1988).

Table 4.5 Monthly rainfall (mm) for Tuapaka and AgResearch, Palmerston North for the November 1995 to February 1997 period compared with the long term monthly rainfall for AgResearch.

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1995												
Tuapaka											93	102
AgResearch											73	101
1996												
Tuapaka	83	110	90	106	117	83	107	113	56	100	110	74
AgResearch	51	129	79	160	115	99	105	82	103	96	101	91
1997												
Tuapaka	67	94										
AgResearch	68	58										
Long Term												
AgResearch	77	58	72	75	93	87	98	86	74	87	82	102

4.5 Exposure

Exposure was measured at 12 positions using the rate of tatter loss of calico cloth flags (warp of 305mm and weft of 380mm) exposed to the elements for nine consecutive bimonthly periods. Flags were initially erected on July 1st, 1998. Tatter loss was measured directly in this study however the British Forestry Commission have developed an indirect method of estimating tatter loss through measurement of the midpoint length (L), or the weft, of the tattered flag using the following equation:

$$\text{Area lost (cm}^2\text{)} = 1161 - 24.91\,L - 0.1039\,L^2 \text{ (Reynard and Low 1984).}$$

The mid point length of each tattered flag was also measured allowing the relationship between mid flag length and tatter loss to be estimated for the flags exposed at Tuapaka. The regression of tatter loss and flag length is shown in Figure 4.4. The relationship is linear and the R^2 value of 0.88 indicates that flag length was potentially a good predictor of tatter loss of cotton flags at Tuapaka. The equation describing the relationship is given below:

$$\text{Area lost (cm}^2\text{)} = 1277.6 - 30.5\,L \quad (R^2 = 0.88).$$

The standard error of predicted tatter loss is 23.0 cm^2

This equation is similar to that utilised by the British Forestry Commission (Reynard & Low 1984). However, a notable difference is the inclusion of a quadratic component in the British equation. A quadratic component was tested in the regression analysis of the Tuapaka data but subsequently excluded because it was not significant and did not improve the coefficient of determination.

The relationship between flag length and tatter loss shows a gap in the data between about 26 and 30cm flag length, leaving three points relatively isolated (Figure 4.4). The regression of Tatter loss on flag length after removal of these points from the data set did not significantly alter the slope or the predicted tatter loss. However, the coefficient of determination was reduced to 0.62.

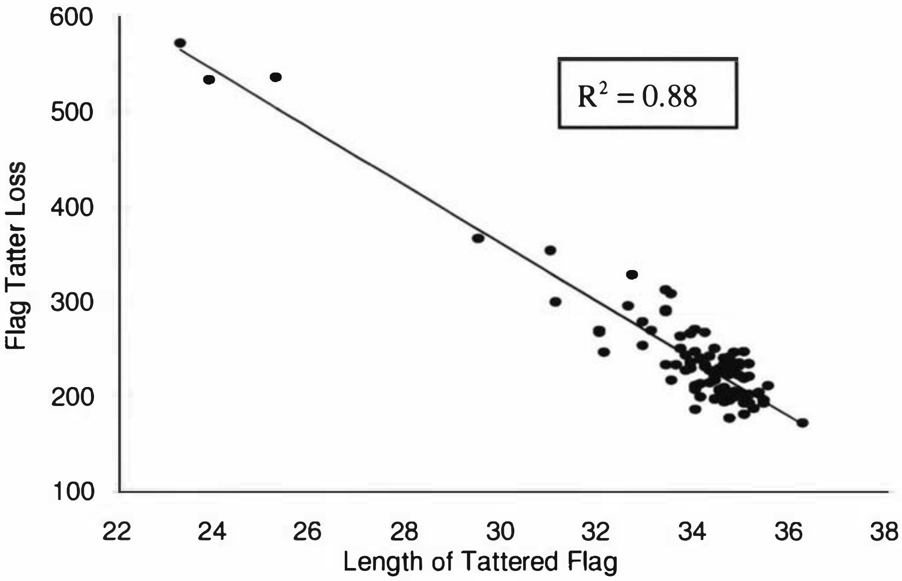


Figure 4.4 The relationship between tattered flag length (cm) and tatter loss (cm^2).

Tatter losses varied with flag position. Flag three experienced greater tatter than any other flag position in each bimonthly measurement period except September/October 1999, when tatter was the same as for flag 10. This resulted in mean daily tatter loss over the 18-month exposure period being significantly greater for flag three than all other flag positions ($P = 0.05$) while tatter rates for flags 10 and 12 were greater ($P = 0.05$) than all remaining flag positions apart from flags six and seven (Table 4.6). Tatter rates also varied with time, generally being highest at the beginning of the monitoring period. The range of tatter loss also decreased towards the end of the monitoring period mostly because tatter losses declined in those flags which had initially experienced large tatter losses, for example flag three. Mean daily windrun in each bimonthly period varied seasonally (Table 4.7), being highest in the late spring/early summer periods and lowest in the winter.

Tatter loss is associated with exposure which can be measured through the TOPEX score; the sum of the angle of inclination to the horizon at the eight main points of the compass. TOPEX score was measured at each flag position (Table 4.8) and ranged from 62 (flag three), the most exposed flag position, up to 171 (flag four), the most sheltered position. Flag three was located on a spur mid way up the slope on the shady face whereas flag four was located in the gully bottom. Flags five and six were also located in the gully but were located nearer the western end closer to the scarp which falls away to the flats and are therefore more exposed. TOPEX was plotted against mean daily tatter loss (Figure 4.5).

To identify the relationship between TOPEX and rate of tatter several non linear regression models were initially tried, including negative exponential and quadratic, however none were satisfactory. Tatter loss appears to show little response to decreasing TOPEX score (increasing exposure) until TOPEX falls to below about 85. This is probably because when TOPEX scores are greater than 85 the flags are sufficiently sheltered to prevent the occurrence of the minimum wind speeds required before flags begin to tatter (Quinn & White 1994). However, when TOPEX drops below about 85 the rate of tatter appears to increase. Consequently a two-piece polynomial or spline model was fitted to the data in Figure 4.5. Spline functions include multiple quadratic polynomial pieces or segments which meet or join at a point sometimes referred to as the 'knot' (Freund & Littell 1986). In two-piece spline models there is a single knot. If the position of the knot is unknown, it can be estimated using non linear regression. In SAS the PROC NLIN procedure is appropriate for this. The NLIN procedure requires initial estimates of the model coefficients as well as an estimate of the knot. From observation of Figure 4.6 the value of the knot was judged to be about TOPEX 85. Initially PROC REG (SAS 1989) was used to estimate the model coefficients. The estimated coefficients from this regression analysis and the estimated knot were then employed to initiate the NLIN procedure (Freund & Littell 1986). This procedure utilises an iterative process to estimate the model coefficients and the value of the knot to achieve the best fit based on minimisation of the residual mean square. The resulting spline equation is given below:

$$\text{Tatter} = 18.253 - 0.2505(\text{TOPEX}) + 0.000923(\text{TOPEX})^2 + 0.0926(A) - 0.00092(A)^2$$
Where A = maximum of (TOPEX - 85.6) and 0.

The position of the knot was estimated to be at TOPEX 85.6, quite close to the initial value of 85. The spline equation has been plotted in Figure 4.5 (Line). There is little change in the rate of tatter above the knot whereas below the knot tatter increases steeply.

Table 4.6 Flag tatter loss (cm^2/day) for each flag in each bimonthly measurement period between August 1998 and January 2000. Values in parentheses are standard errors of the mean for each flag.

		1998				1999/2000				
Flag	AS	ON	DJ	FM	AM	JJ	AS	ON	DJ	Mean
1	2.6	3.5	3.3	3.3	3.8	3.2	3.5	3.9	3.4	3.38 (0.12)
2	2.6	3.7	3.4	3.4	4.0	3.3	3.6	3.8	3.5	3.48 (0.13)
3	6.4	8.9	4.9	4.9	5.9	5.5	5.0	4.5	4.4	5.60 (0.47)
4	2.4	4.7	3.3	3.3	3.8	3.6	3.4	3.3	3.6	3.48 (0.20)
5	2.5	3.9	3.0	3.0	3.5	3.4	3.8	2.9	3.4	3.26 (0.15)
6	2.5	4.5	3.5	3.5	3.9	3.3	4.0	4.1	3.3	3.62 (0.20)
7	2.6	4.5	3.4	3.4	3.9	3.5	3.7	3.4	3.3	3.52 (0.17)
8	2.2	4.2	3.3	3.3	4.2	3.3	3.4	3.9	3.6	3.48 (0.21)
9	2.4	3.4	3.5	3.5	3.7	3.5	3.6	4.1	3.4	3.45 (0.15)
10	3.0	5.0	3.9	3.9	4.2	5.2	4.2	4.5	3.4	4.14 (0.24)
11	2.7	4.3	3.1	3.1	3.7	3.7	3.4	4.2	3.1	3.47 (0.18)
12	3.5	6.1	4.0	4.0	4.0	4.4	4.1	3.4	3.2	4.08 (0.29)

Table 4.7 Mean daily wind run (km/day) at AgResearch, Palmerston North for each bimonthly measurement period between August 1998 and January 2000.

	1998			1999/2000					
	AS	ON	DJ	FM	AM	JJ	AS	ON	DJ
Windrun	154	267	312	241	211	183	190	256	257

Table 4.8 TOPEX score for each flag position.

	Flag											
	1	2	3	4	5	6	7	8	9	10	11	12
TOPEX	95	85	62	171	148	129	94	111	98	78	82	82

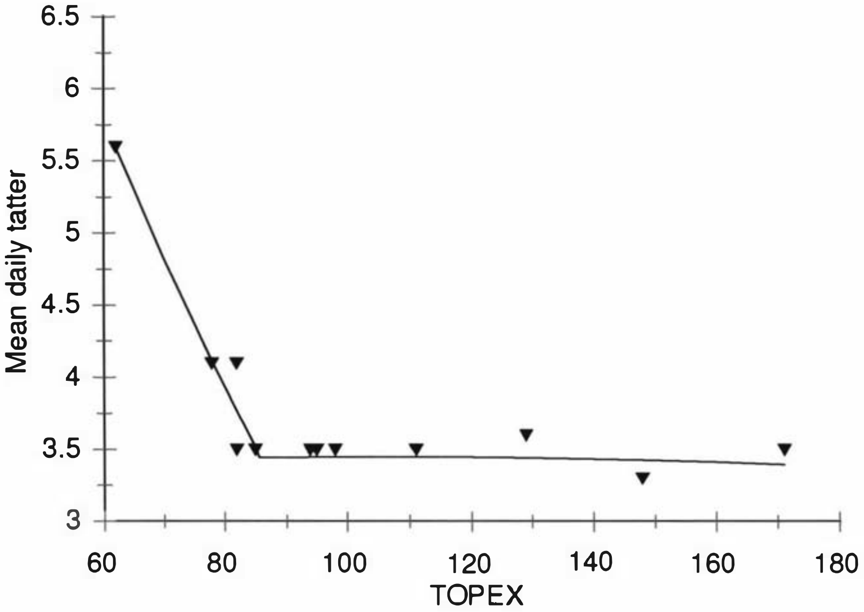


Figure 4.5 The influence of TOPEX score on mean daily flag tatter loss (cm^2/day) between August 1998 and January 2000.

4.6 Discussion

4.6.1 Radiation and temperature

Differences in mean temperature between aspects varied with season, being greatest in the winter months, but was always less than 1°C, and least in the warmer months when differences were typically insignificant. These differences are lower than those found in some other New Zealand studies. For example in North Canterbury Radcliffe and Lefever (1981) estimated mean daily air temperature for July to be 9.4 and 3.4 °C for the sunny and shady aspects respectively, and during January, 17.5 and 15.4°C for the sunny and shady aspects, respectively. Consequently the estimated annual mean daily temperature was 13.7°C on the sunny aspect and 9.9°C on the shady aspect, a difference of 3.8°C. In contrast the mean annual daily temperature at Tuapaka was 12.8°C and 12.4°C (1996/7), and 13.3°C and 12.8°C (1997/98) for the sunny and shady face, respectively. On the other hand Lambert and Roberts (1976) found that air temperatures on different aspects in hill country at Ballantrae in the southern Ruahine range (near Woodville), were similar. Aspect temperature differences are the result of differences in the amount of incoming solar radiation (White 1990). With the exception of those months around the summer solstice solar radiation was greater on the sunny face, relative differences being greatest in the winter months when the sunny face received between 25% and 63% more radiation than the shady face (Table 4.4). The sunny face received 10.0% and 20.4% more annual radiation than the shady face in 1996/97 and 1997/98, respectively. In the North Canterbury study the sunny aspect received 80% more solar radiation than the shady over a 12-month period (Radcliffe & Lefever 1981), a considerably larger relative difference than at Tuapaka.

Waikato research (Whatawhata) showed that aspect differences in air and soil temperatures were greater under clear conditions than cloudy (Gillingham & Bell 1977), cloudy conditions buffering temperature extremes by reducing the relative difference in aspect radiation. These authors noted that cloudy days had more wind than clear. Wind was negatively correlated with radiation at Tuapaka (Table 4.9). Wind also buffers temperature, obscuring the effect of radiation on aspect temperature (Lambert & Roberts 1976). Cloudy, windy conditions are relatively common in the Manawatu, particularly in the northern Tararua Range (Burgess 1988). This suggests that the relatively small aspect effect on temperature at Tuapaka is probably due to relatively small differences in solar radiation resulting from the prevalence of cloud cover and wind at the site. This is supported by an association between aspect mean daily temperature difference (Table 4.2) and solar radiation. The correlation coefficient (Table 4.9) between aspect temperature difference and aspect radiation difference and wind run (AgResearch) shows moderately strong positive associations between aspect temperature difference and aspect solar radiation difference in both 1996/97 and 1997/98. However, wind reduced the difference in aspect temperature in both years.

Table 4.9 Pearson correlation coefficients between aspect mean daily temperature difference (°C), aspect daily radiation difference (MJ/m^2/day) and AgResearch wind run (km) during 1996/97 and 1997/98. Numbers in parentheses are probabilities.

		Δ Aspect Radiation	Wind
Δ Aspect Temperature			
	1996/97	0.82 (0.0001)	-0.62 (0.03)
	1997/98	0.66 (0.02)	-0.71 (0.01)
Wind			
	1996/97	-0.71 (0.01)	
	1997/98	-0.49 (0.10)	

Aspect differences in annual mean daily radiation can result in significant effective latitudinal displacement, particularly in the middle latitudes (Holland & Stein 1975). Radcliffe & Lefever (1981) estimated that the difference in radiation on northerly and southerly slopes in north Canterbury resulted in an annual mean daily temperature difference that was equivalent to about 9° of latitudinal displacement. Aspect mean annual temperature difference (1996/97 and 1997/98) at Tuapaka was 0.5°C, less than that found in the above study. Differences of this magnitude for sites at a similar altitude can be seen when comparing AgResearch, (annual mean daily temperature 12.9°C, altitude 34m, latitude 40° 23S) and Greymouth (12.3°C, 4m, 42° 28S) or Appleby (12.5°C, 17m, 41° 17S) (NZ Meteorological Service 1983). This suggests a latitudinal displacement of between 1 and 2°. It might also result from a difference in altitude of about 100m (Burgess 1988).

Radiation received on the sunny face in 1996/97 and 1997/98 (mean 12.0 MJ/m^2) is comparatively low, a reflection of the typically cloudy conditions in the ranges (Burgess 1988) and can be likened with sites much further south such as Dunedin (12.4 MJ/m^2) and Invercargill (12.6 MJ/m^2) (NZ Meteorological Service 1983).

Minimum temperatures were relatively mild with few air frosts. Minimum temperatures in hill country are often warmer than on surrounding flat land because cold air is able to drain off sloping ground. The incidence of frost is greatest during the winter months on clear, calm nights (Burgess 1988) but the frequency of cloudy, windy conditions results in buffering of minimum temperatures, reducing the incidence of frost. Cloud cover elevates minimum temperatures by reflecting long wave radiation back to the earth surface while wind results in continual displacement of cold air by warm air (Miller 1966). The surrounding ocean, over which wind reaching New Zealand has passed, has a significant warming effect in New Zealand (Burgess 1988). Minimum winter temperatures at Tuapaka (shady face) were correlated with radiation (sunny face) and wind (AgResearch) in all years (Table 4.10).

Table 4.10 Pearson correlation coefficients between winter (June to August) minimum daily temperature (°C), mean daily solar radiation (MJ/m^2/day) and AgResearch wind run (km) from 1996 to 1998. Numbers in parentheses are probabilities.

	Radiation	Wind
Winter Minimum temperature		
1996	-0.41 (0.0001)	0.45 (0.0001)
1997	-0.25 (0.02)	0.39 (0.0001)
1998	-0.54 (0.0001)	0.26 (0.01)

Minimum temperature is moderately positively correlated with wind run but negatively correlated with solar radiation. Solar radiation is an indirect measure of night time cloud as it assumes that a clear sunny day (high radiation) is preceded by a clear night. Gillingham & Bell (1977) found that the probability of clear sunny days following a clear sunny day was greater than for a cloudy day; this implies that a clear day would be more likely to be preceded by a clear night than a cloudy night. Clear weather is mostly associated with high pressure anticyclones which typically take several days to pass over the country (Burgess 1988).

4.6.2 Rainfall

The rainfall data collected at Tuapaka is limited. Monthly rainfall totals were similar to those recorded at AgResearch. Although the trial site is on the western flanks of the northern Tararua Range, which experiences higher rainfall than the Manawatu Plains due to local orographic effects, at 120 to 140 m altitude it is not in the high rainfall belt nearer the peak of the range (Burgess 1988). Rainfall during individual rain events can be strongly influenced by aspect depending on the direction and strength of associated winds (Radcliffe & Lefever 1981). However, in the longer term aspect differences tend to balance resulting in rainfall being similar on all aspects (Lambert & Roberts 1976; Radcliffe & Lefever 1981).

4.6.3 Exposure

Exposure was measured by exposing cotton tatter flags for 60 day periods and measuring the loss in flag area at the end of the exposure period. Tatter area was measured directly and indirectly by measuring the flag weft. Measuring length loss is a quick and simple way of estimating tatter area but it may not be as reliable as direct measurement. For example, Rutter (1966) found that measurement of length was the most variable of three techniques (area loss, weight loss and length loss) for estimating flag tatter. However, in some situations, in particular very exposed sites, flag length loss can be as reliable as area or weight loss measurements (Rutter 1968). Rutter (1968) found that the coefficient of determination between length and area loss was 0.994 and 0.932 for trimmed and untrimmed flags respectively. Trimming flags involves removing the fray at the end of the flag, which acts by protecting the flag from tattering at low wind speeds, making flags more sensitive to light winds (Rutter 1966). The coefficient of determination between flag length and area loss in the current study was 0.88, broadly comparable with Rutter (1966). The convenience of flag length measurement has seen it become a standard technique for assessing exposure using tatter flags in Britain (Reynard & Low 1984).

Tatter rates at Tuapaka ranged between 3.3 cm^2/day and 5.6 cm^2/day. These tatter rates cannot be directly compared with those recorded in Britain for example because the material used (calico) is not identical to the standard flag material (madapollam) utilised in most overseas research. They are similar in that both are made from plain cotton but madapollam is made from bleached cotton and is primarily used for women's clothing whereas calico is unbleached and is a heavier fabric (The Textile Institute 1991). Tatter rates for madapollam flags in Britain tend to be least in the south east and greatest in the north at exposed high altitude sites where tatter rates up to 18.2 cm^2/day have been measured (Quine & White 1994). The key environmental factor influencing rate of tatter is windiness (Rutter 1966; Rutter 1968) both total wind run and the occurrence of very strong winds (McAdam 1980). Although wind was not measured at Tuapaka wind run is measured at AgResearch, Palmerston North (Table 4.7). Variations in mean daily wind run at AgResearch between August 1998 and January 2000 was typical of the Manawatu, being generally greater during the late spring early summer period and lowest during the winter months (Burgess 1988).

Tatter rates showed little sensitivity to exposure over a wide range of TOPEX values but more exposed flags at higher elevation experienced increased tatter rate. Increasing rates of tatter in response to increasing altitudes has been previously found in New Zealand (Linklater et al 2000) and in Britain (Thomson 1984) and this is usually associated with decreasing TOPEX scores. However, TOPEX scores may also be low at low altitude sites on plains meaning that assessment or comparison of different sites for exposure using TOPEX can be misleading unless other geographical variables, such as terrain, are not taken into account (Quine & White 1994).

There was considerable variation in tatter rates in each bimonthly period (Table 4.6). This was consistent with the variation in climatic conditions also experienced. Some researchers have found that most of the variation in tatter rate between measurement periods is associated with wind (McAdam 1980) while others have found that rainfall is also important (Rutter 1966; Rutter 1968). McAdam (1980) worked in the Falkland Islands where flags were exposed to less rain than when Rutter (1968) exposed his flags. The mean tatter rate for each measurement period at Tuapaka was correlated with a number of meteorological variables recorded at AgResearch; mean wind speed, number of days with wind gusts of Beaufort force four or greater (New Zealand Meteorological Service 1984), total rainfall and number of days when rainfall was above 1.0 mm (Table 4.11).

Table 4.11 Pearson correlation coefficients between the mean rate of flag tatter (cm^2/day) at Tuapaka and mean wind speed (km/hr), number of days when wind was at Beaufort force four or greater, total rainfall (mm) and number of days > 1mm rain at AgResearch. Numbers in parentheses are probabilities.

	Wind	Force 4	Rainfall	Raindays
Tatter	0.32 (0.4)	0.49 (0.18)	0.71 (0.04)	0.31 (0.41)

Tatter rate is significantly correlated with rainfall but none of the other coefficients are significant, partly because of the limited size of the data set (nine measurement periods). Rutter (1966) found that wet flags tattered at a faster rate than dry flags under laboratory conditions and under field conditions (Rutter 1968). This was because wet flags experienced more sideways movement when fluttering, meaning that velocities at the fraying end were higher than for dry flags. He also found that wet flags, being heavier, are less sensitive to lighter winds than dry flags. As a consequence wet, windy weather may result in an overestimation of exposure for flags in relatively exposed positions. The correlation between rainfall and the number of days with force four or greater wind gusts in each measurement period at AgResearch was 0.56 (P = 0.12). Wind direction may also affect tatter if the probability of rain is influenced by wind direction (Rutter 1968). The most prevalent winds in Manawatu come from the northwest and typically result in shower activity especially over or near the ranges. (Burgess 1988).

4.7 Summary

There were significant aspect differences in mean daily solar radiation, the sunny face receiving more radiation than the shady. Differences varied with the season, being greatest in the winter months and least in the summer months. Consequently, mean air temperatures were greater on the sunny face in most months. This was primarily due to higher maximum temperatures on the sunny face; aspect differences in minimum temperature were generally small. However, aspect differences in radiation and mean temperature were not as large as have been found in other New Zealand comparisons. This is probably a reflection of the prevalence of cloudy and windy weather at Tuapaka, which buffers temperature extremes. Exposure was assessed by estimation of TOPEX scores and by the rate of tatter of cotton flags on different microsites. TOPEX scores were highest in the gully bottom and declined with increasing elevation. Tatter rates showed little response across a range of TOPEX scores from the more sheltered positions but exposed positions at higher elevation experienced significantly increased tatter.

Chapter 5

Establishment

5.1 Introduction

Establishment is a critical phase of afforestation; poor establishment may result in the need to replant in the following year, incurring additional costs and the loss of one year's growth (Maclaren 1993). High death rates may result from weed competition, drought as well as pest damage (McCarthy 1980; Maclaren 1993). Many of the alternative species (to *Pinus radiata*) in New Zealand, including eucalypts, have generally suffered relatively poor survival rates compared to those achieved with *P. radiata*, particularly if site factors are challenging (Poole & Fry 1980; Burdon & Miller 1995; Maclaren 2005). Assessment of seedling survival was scheduled to occur at the end of the first summer to identify any species and microsite differences and also to allow effective blanking of the trial. The incursion of pests shortly after planting meant that monitoring of pest activity was also necessary in order to make judgements about whether or not control measures were necessary and also to assess the impact of pest damage; immediate potential impacts included reduced survival and longer term impacts, effects on tree growth.

5.2 Methods

After planting seedlings generally showed good growth and vigour. Planting spots remained clear until mid summer (Plate 5.1). The first plants to reappear in the planting spots were black nightshade (*Solanum nigrum*) and scotch thistle (*Cirsium vulgare*); however no further weed control was carried out because weed growth was light and did not appear to be seriously competing with the tree seedlings. In mid-November browsing damage in a few seedlings was becoming apparent. The browsing was attributed to possums (*Trichosurus vulpecula*). Browsed leaves typically were almost completely defoliated but with much of the midrib and major veins left so that only a leaf skeleton remained (Plate 5.2), characteristic of possum damage (Pracy & Kean 1969). Possum faecal pellets were also present. By early December 1995 the incidence of browsing began to increase and a decision was made to control possums to minimise the risk of widespread seedling losses. Pelletised cereal bait containing an anticoagulant poison (0.02 g/kg brodifacoum) was laid using bait stations to kill possums in December 1995. Brodifacoum is highly effective against possums, having an LD_{50} of 0.4 mg/kg of body weight (Eason & Wright 1998). The bait was enthusiastically accepted and by early January 1996 nearly 20 kg of bait had been fed, after which bait disappearance was negligible: This brought browsing damage to a halt. The incidence of browse damage was determined by inspecting every seedling in mid December 1995 and late January 1996. This was undertaken to assess any possible treatment effects on browsing damage and also to allow the use of browse incidence scores as a covariant to help control experimental error (Steel & Torrie 1980). Seedlings were assessed as browsed or not browsed. On the 15th of March 1996 survival of all seedlings was recorded but without any assessment of vigour. This information was then used to calculate the % of seedlings that had suffered browsing and % deaths for each plot.

An inherent problem with categorical data is that it may not be normally distributed, a key requirement for parametric statistical analysis. A check of the frequency distributions of the browsing and survival data revealed that they were strongly skewed (Figure 5.1). In an attempt to correct this problem the data were transformed, initially by taking the arcsine and secondly the square root (Steel & Torrie 1980) of the plot means for % browsed and % deaths, but both transformations failed to correct the skewness. Consequently, a non parametric analysis was used to test for differences among treatment means. The Wilcoxon signed-rank test (Steel & Torrie 1980) was selected for this purpose because it does not require data to be normally distributed and it provides for the calculation of a test statistic which can be compared with critical values to test for differences between pairs of observations. Normally distributed data is not required because the test is based on the rank order of the differences, rather than the numerical differences (for example the *t* test), between pairs of observations. An example of the procedure used for Wilcoxon's test is given in Appendix 6.

To examine any relationship between browse damage and survival, Pearson rank correlation was calculated. Pearson rank correlation also utilises ranks, measuring the correspondence between the ranks of each variable (Steel & Torrie 1980). Its use is appropriate when a key requirement for simple correlation is not met, namely that the data being analysed comes from a bivariate normal distribution (Everitt & Der 1996).

Plate 5.1 A planting spot, four weeks after planting (*E. nitens*).

Plate 5.2 Possum browse damage on *E. microcorys* seedling, November 1995

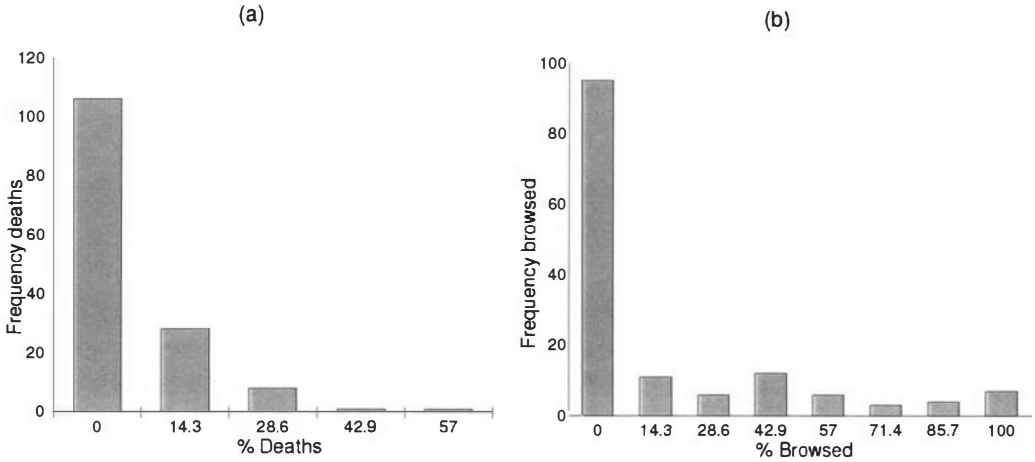


Figure 5.1 Frequency distribution (number of plots) for (a) % deaths and (b) % browsed of *Eucalyptus* seedlings in each plot.

5.3 Browse damage

Characteristic browsing damage included significant defoliation as well as removal of the apical shoot on many seedlings. Browsing was widespread in *E. microcorys* (Table 5.1) with greater than 50% of seedlings suffering browse damage, more than twice the incidence of the second most browsed species, *E. saligna*. The lowest incidence of browse damage occurred in *E. cladocalyx* (3.0%). Damage to a few seedlings appeared to be due to hares (*Lepus europaeus*), which typically results in stems of seedlings being bitten through and left (Porteous 1993). However, no control of hares was carried out because the damage was very limited and because hares are very elusive animals. The affected seedlings recovered.

Table 5.1 The effects of species, slope aspect and slope position on the % of seedlings suffering possum browse damage.

	Aspect			
	Shady		Sunny	
Position	Upper	Lower	Upper	Lower
E. agglomerata	0	0	61.4	4.3
E. baxteri	0	0	67.1	4.3
E. botryoides	0	0	71.4	10.0
E. cladocalyx	0	0	14.3	0
E. globoidea	0	0	18.6	14.3
E. microcorys	32.9	10.0	90.0	4.3
E. muelleriana	0	0	38.6	14.3
E. nitens	0	0	38.6	57.1
E. obliqua	0	0	10.0	10.0
E. pilularis	0	0	18.6	32.9
E. regnans	0	0	4.3	18.6
E. saligna	0	0	75.7	32.9
Mean	2.7	0.8	42.4	16.9
SEM	2.7	0.8	8.5	4.8
Median	0	0	38.6	12.2

Browsing was much more prevalent on the sunny face than the shady face (Table 5.1). Wilcoxon's test indicated that the effect of aspect was highly significant ($P < 0.01$). On the sunny face the proportion of seedlings suffering damage was significantly higher on the upper slope than on the lower slope ($P = 0.05$). A worked example of Wilcoxon's test for this comparison is shown in Appendix 6. *E. microcorys* suffered significantly more browse damage ($P = 0.03$) than all other species, particularly on the upper sunny face where 90% of seedlings were browsed and it was the only species browsed on the shady face. Damage was relatively light in *E. cladocalyx*, *E. obliqua* and *E. regnans*.

5.4 Seedling survival

Seedling deaths were generally low, less than 5% in most species, and mostly occurring on the sunny face (Table 5.2). An exception to this was *E. cladocalyx* which suffered losses ranging from 9.5% to 19%, being highest on the shady face. There was no difference between *E. cladocalyx* and *E. regnans*, the 2nd ranked species for seedling deaths and the only other species to suffer losses on all microsites. However, there was a significant difference between *E. cladocalyx* and *E. obliqua* ($P = 0.02$), the 3rd ranked species for seedling deaths. There were no detectable slope position effects on seedling deaths. In contrast the effect of aspect was significant for both slope positions ($P = 0.01$), the sunny face suffering more losses than the shady.

Table 5.2 The effects of species, slope aspect and slope position on seedling deaths (%), March 15th, 1996.

	Aspect			
	Shady		Sunny	
Position	Upper	Lower	Upper	Lower
E. agglomerata	0	0	9.5	4.8
E. baxteri	0	0	4.8	19.0
E. botryoides	0	0	4.8	14.3
E. cladocalyx	19.0	19.0	9.5	14.3
E. globoidea	4.8	0	4.8	4.8
E. microcorys	0	4.8	0	9.5
E. muelleriana	0	0	0	4.8
E. nitens	0	0	4.8	4.8
E. obliqua	0	9.5	0	19.0
E. pilularis	0	0	4.8	4.8
E. regnans	4.8	4.8	19.0	4.8
E. saligna	0	0	4.8	4.8
Mean	2.4	3.2	5.6	9.1
SEM	1.7	1.7	1.6	1.7
Median	0	0	4.8	4.8

5.5 Discussion

5.5.1 Survival

With the exception of *E. cladocalyx* survival rates to March 1996 were generally good, achieving rates comparable with those achievable with *P. radiata*. Survival at six months of good quality, carefully handled, bare rooted *P. radiata* seedlings planted within a few days of lifting using good planting techniques can be close to 100% in New Zealand (Forest Research Institute 1978; Maclaren 1993). In a series of trials on the West Coast comparing a range of *E. nitens* provenances as well as single provenances of *E. obliqua*, *E. regnans*, *E. delegatensis* and *E. fastigata* Franklin, (1980) found considerable variation in survival amongst species and provenances of containerised seedlings. Survival of over 90% one year after planting were the exception, even on the best site, and were typically less than 80%. Hathaway & King (1986) compared a large number of eucalypt species potentially useful for slope stabilisation on two sites in summer dry Wairarapa hill country at Pakaraka and Kahuiti. Survival at the end of the first summer was 81% at Pakaraka and 66% at Kahuiti and was generally associated with vigour of trees at each site. Differences in survival of individual species were much greater however, ranging from 100% at both sites down to 20% at Kahuiti and 43% at Pakaraka. The poorest species at Kahuiti was *E. cladocalyx* whereas this species had relatively good survival at Pakaraka and was one of the best species for early height growth.

Many eucalypt species can be planted as bare rooted seedlings but survival is often lower than container grown stocks, particularly when planted on harsh sites or when planting late to avoid winter frosts (Hathaway & Sheppard 1996). Bare rooted seedlings generally cost less to produce than container grown and thus are normal for the large scale planting of eucalypts (Forest Research Institute 1982). However, bare rooted seedlings of some eucalypt species, for example *E. pilularis*, are very difficult to produce and handle, necessitating the use of containerised grown stock (McWhannell 1960; Barr 1996; Hathaway & Sheppard 1996).

Low survival in *E. cladocalyx* may be a result of *Botrytis cineria* infection, which had infected many seedlings when in the glasshouse, and had persisted after planting in this species. *B. cineria* is a very common plant pathogen infecting the stems, leaves, flowers and fruit of a wide range of plants, including *Eucalyptus* (Stone et al 1998). It is a recorded nursery disease of many tree species in New Zealand including *Eucalyptus* and may occasionally cause mortality (Dick & Vanner 1986). Franklin (1980) attributed high mortality in *E. nitens* on the West Coast of the South Island to residual *B. cinerea* infection of seedlings.

Incidences of poor survival of eucalypt seedlings have been attributed to a number of factors including poor weed control (Low & Shelbourne 1999), fungal disease, snow (Turnbull et al 1993) frost (Johnson & Wilcox 1989) and moisture stress (Hathaway & King 1986). Most seedling deaths had no obvious cause but greater losses on the sunny face indicate that soil moisture stress may have been a factor. Total rainfall recorded at the trial site during the five-month period from November 1995 to February 1996 was 357 mm, evenly distributed. However evapotranspiration in Manawatu over the January/February period is typically greater than rainfall resulting in soil moisture deficits and these deficits can be quite severe on sunny faces in hill country, limiting plant growth (Cowie 1978; White 1990). While evapotranspiration was not measured potential evapotranspiration can be estimated from solar radiation, temperature, wind and vapour pressure (Allen et al 1998). Of these only temperature and radiation were measured (Chapter 4), however Scotter & Heng (2003) found that potential evapotranspiration in Manawatu was strongly correlated (R^2 range from 0.72 to 0.75) with solar radiation over the summer period. Solar radiation on the sunny face during the October to March period (Figure 4.3a and 4.3b) was greater than on the shady face in 9 months out of 12 for the two years recorded. This indicates that evapotranspiration on the sunny face over the summer period is typically greater than on the shady face and that increased moisture deficit on the sunny face probably contributed to higher mortality (Lambert & Roberts 1976).

5.5.2 Browse damage

Browsing of eucalypts by possums has been reported from many regions in New Zealand (Pracy & Kean 1969). Occasionally damage can be persistent and severe in preferred species resulting in significant losses (Shelbourne et al 2000). Browsing damage was almost entirely confined to the sunny face, particularly the upper slope. While this suggests an aspect affect on browsing damage it may also be the result of the close proximity of seedlings on the sunny face to an 8 ha stand of *P. radiata* in the neighbouring catchment. *P. radiata* plantations harbour possums in low to moderate densities, depending on the availability of den sites rather than food availability (McLaren 1996). The neighbouring stand is on very steep country with flax and gorse present on the steepest areas, both of which provide opportunities for den sites. (Pracy & Kean 1969). The proximity to cover used by possums can influence the extent of browse damage of palatable plants including young eucalypt trees (Bulinski & McArthur 2003).

There was a strong preference shown for *E. microcorys* seedlings. Preferential or selective browsing of different tree species is a characteristic of possum feeding (Shelbourne et al 2000; Marsh et al 2003) but this may change from district to district and at different times of the year (Pracy & Kean 1969). *E. microcorys* is a *Symphyomyrtus* species (Chapter 3) which are preferred by possums over trees from the *Monocalyptus* subgenus, due to typically high tannin content in the foliage of *Monocalyptus* species (Marsh et al 2003). However *E. cladocalyx*, also a *Symphyomyrtus* species, was only lightly browsed. Selection of individual species may be the result of differences in the concentration of a number of phenolic compounds in the foliage including tannin and lignin (McArthur et al 2003) and diformylphloroglucinols, a group of compounds, new examples of which are still being described, found in the foliage of some *Eucalyptus* species and which deter possum browsing (Lawler et al 1999a). Of the known diformylphloroglucinols high concentrations of sideroxylonal (a high molecular weight diformylphloroglucinol) has been shown to depress intake of eucalypt foliage by marsupials (Eschler & Foley 1999). A survey of 41 *Eucalyptus* species identified sideroxylonal as the most commonly found diformylphloroglucinol (Eschler et al 2000). This survey found high concentrations in *E. microcorys*, the most browsed species in this trial, whereas concentrations were low in surveyed *E. cladocalyx*, the least browsed species. However, a less common simple (low molecular weight) diformylphloroglucinol, jensenone, which also has a strong deterrent effect on possum browsing (Lawler et al 1999b), was not detected in *E. microcorys* but was found in *E. cladocalyx*. Appreciable intraspecific variation in diformylphloroglucinols (Lawler et al 1998; Eschler et al 2000) means that interpretation of results from a single survey with a small sample size (n = 4) has to be treated with caution.

Correlation analysis revealed that browsing had no effect on survival (r = 0.16). *E. cladocalyx* suffered the least browse damage of any species yet had the highest death rate. Conversely, the death rate in *E. microcoys* was relatively low but suffered more browsing than all other species. Browsing by common brush-tail possums and other marsupials can be a serious problem in Australian *Eucalyptus* plantations, however most Australian research has found that short term browsing has little if any influence on seedling survival (Bulinski 1999; Bulinski & McArthur 1999; McArthur & Appleton, 2004). However long term browsing, often the result of insect feeding rather than mammals, may increase mortality (Turnbull et al 1993). Browsing of seedlings in natural eucalypt forest can cause significant mortality (Abbott 1984) and is associated with increased competition faced by young seedlings in natural forests (Florence 1996).

5.6 Summary

Survival of seedlings to six months of age was generally good, all species except *E. cladocalyx* achieving survival rates of greater than 90%. Most losses occurred on the sunny aspect, probably because of lower soil moisture content on that aspect, however, slope position had no influence on survival. Seedlings of all species suffered from possum browsing after planting but browsing did not influence survival. Browsing damage was highest in *E. microcorys*, which was browsed on all microsites, but for all other species browsing was confined to the sunny aspect, predominately the upper slope.

Chapter 6

Foliar Nutrients

6.1 Introduction

This chapter investigates the influence of slope aspect and slope position on the foliar concentration of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) of each tree species. The influence of subgenera on foliage nutrient concentrations will also be explored. Nutrient correlations for different species, subgenera and microsites will be compared.

Many *Eucalyptus* species grown in plantations are sensitive to low nutrient availability, particularly N and P (Schönau & Herbert 1989). Nitrogen fertilisers have been shown to be beneficial in eucalypt plantations during the establishment period and their general use is recommended at or soon after planting in New Zealand (Knight & Nicholas 1996) and in many overseas countries (Herbert 1996; Pereira et al. 1996; Prado and Toro 1996; Wang & Zhou 1996). On low fertility sites additional applications of fertiliser may be warranted (Pool & Fry 1980; Schönau & Herbert 1989; Judd et al. 1996b; Knight & Nicholas 1996) at least up until canopy closure when nutrient availability becomes more dependent on nutrient cycling (Miller 1981). New Zealand studies have found responses to N only, P only and responses to N only if P is also applied (Knight & Nicholas 1996). For example, Pool and Fry (1980) found that on pumice soils of the volcanic plateau only N was required while Bunn (1962) found that both N and P were beneficial on Northland clay soils, reflecting the chemical characteristics of each soil.

The concentration of foliar nutrients is potentially a useful indicator of the nutritional status of individual trees, stands and plantations. Consequently some countries have developed critical nutrient levels for the most commonly planted eucalypt species which are used to help with decisions on the economics of fertiliser applications

(Schönau & Herbert 1989). There is little information on critical or normal foliar nutrient concentrations for most eucalypts in New Zealand, however Knight & Nicholas (1996) have published provisional macronutrient and micronutrient norms for two and three year old stands of *E. delegatensis, E. regnans* and *E. saligna* in New Zealand.

The availability of nutrients to young *Eucalyptus* trees (and all plants) is initially mostly determined by soil fertility and later on by the cycling of nutrients in the soil-plant system (Miller 1981; Frederick et al 1985). Slope aspect and slope position are known to influence various soil characteristics, which in turn may affect plant growth, including depth, fertility, temperature and moisture (White 1990). Gradual downhill movement of colluvium over long periods of time can result in soil and associated nutrients moving from upper to lower slopes, increasing soil depth, fertility and water holding capacity (Florence 1996). Much of New Zealand's deforested hill country has suffered periodic landslip erosion characterised by rafting of soil downslope, resulting in accelerated accumulation of soil on lower slopes and reduced soil depth on the upper and mid slopes (Trustrum & De Rose 1987). On shady aspects lower solar radiation results in lower air and soil temperatures compared with sunny aspects for much of the year and therefore reduced annual pasture growth, particularly in summer wet regions (Suckling 1975). However in summer dry regions shady aspects may be more productive than sunny aspects on an annual basis and during the summer and autumn seasons in particular because of higher soil moisture resulting from lower evapotranspiration (White et al. 1972; Radcliffe & Lefever 1981). Over long periods of time the grazing habits of sheep and cattle on hill country results in the transfer of nutrients from the least grazed areas, which tend to be steep, to areas with less slope used as camps (Gillingham & During 1973). These aspect differences alter the botanical composition of hill country pastures (White et al 1972).

Soil tests can help characterise the fertility status of soils and consequently help identify the potential for economic yield increases from fertiliser application to eucalypts (Knight & Nicholas 1996).

The natural range of the eucalypts varies from very infertile through to fertile and species adapted to these different site conditions vary tremendously in their ability to acquire and utilise nutrients for growth (Kriedemann & Cromer 1996). Knowledge of the response of different *Eucalyptus* species and subgenera to soil fertility is potentially very useful for management purposes in both natural (Beadle 1962; Judd et al 1996a) and plantation forests (Judd et al 1996b). The distribution of different eucalypt species in the higher rainfall areas of the eastern coastal strip of Australia is mostly determined by soil fertility, particularly P (Beadle 1962). Species from the *Monocalyptus* subgenus tend to dominate in low fertility areas whereas those from the *Symphyomyrtus* subgenus dominate on more fertile soils (Florence 1996). A typical example of this pattern is the association between *E. pilularis* and a 'mix' of hardwood species, including *E. microcorys* and *E. saligna*. *E. pilularis* tends to dominate in the low fertility areas, which are often linked with a particular parent material, while the mixed community dominates when soil fertility is higher (Florence 1964). This fertility gradient may also be determined by slope position; *E. pilularis* is often found on upper slopes, giving way to *Symphyomyrtus* species lower down the slope where, again, soils are more fertile (Florence 1996). While some authors have claimed that the ecological distinctions between eucalypt subgenera mean that they are also nutritionally different resulting in, for example, greater nutrient concentrations in *Symphyomyrtus* compared with *Monocalyptus* species (Davidson & Reid 1980; Noble 1989), Judd et al (1996a) concluded that for the most important nutrients (N & P) the available evidence did not justify such a conclusion. However, these authors did find evidence of higher concentrations of K and Ca in the foliage of *Symphyomyrtus* species, and higher concentrations of Mg in the foliage of *Monocalyptus* species.

Foliar nutrient analysis was undertaken to determine the effects of microsite and species on foliar nutrient concentrations and to identify any characteristic nutrient profiles at the species and subgeneric level. Relationships between concentrations of individual nutrients for species, subgenera and microsite are also investigated. Relationships between foliar nutrient concentrations and growth and form are examined in Chapter 7.

6.2 Methods

The procedures used to collect foliage and analyse foliage are outlined in detail in Chapter three (Section 3.7.3). Foliage nutrient data were subject to analysis of variance to test for differences among species and microsites and also to detect possible interactions between these factors. In addition the ratio of nitrogen to phosphate (N:P) was analysed. This nutrient ratio has been found to be usefully associated with eucalypt productivity (Schönau 1981; Judd et al 1996a). Orthogonal contrasts were used to test differences in mean nutrient concentration between subgenera and between the ash and stringybark groups within *Monocalyptus*. Correlation analysis was used to explore any relationships between foliar nutrients for different species, subgenera and microsites. Subgeneric differences in the nutrient correlation matrices were explored. Tests for homogeneity of correlation coefficients were carried out using the procedure outlined in Steel & Torrie (1980), page 280.

A principal component analysis was also used to simplify the nutrient data, allowing identification of underlying dimensions in the data to be more readily achieved. For example, identification of subgeneric differences in foliar nutrient profiles. Principal component analysis is a multivariate technique which facilitates the reduction in the number of correlated variables necessary to summarise a data set, allowing trends or differences in the data to be more easily recognised (Ganesalingam 1992). If the variables are not correlated however, there is little point in this analysis (Manly 1994). The Tuapaka nutrient data consists of five variables which are inter-correlated, complicating interpretation of the data. Principal component analysis reduces the number of variables required to explain the underlying variation in the data by calculating indices, or principal components, which are uncorrelated but a small number of which explain a large proportion of the variation in the original data. Lack of correlation between components is highly desirable because it means that each is measuring a different facet of the data (Manly 1994).

Principal component analysis looks for combinations of variables to produce principal components, the number of which equals the number of variables, using a linear combination of the variables, in this case N, P, K, Ca and Mg. The forms of the linear functions for the principal components are shown below.

$$PC_1 = a_{11}N + a_{12}P + a_{13}K + a_{14}Ca + a_{15}Mg$$
$$PC_2 = a_{21}N + a_{22}P + a_{23}K + a_{24}Ca + a_{25}Mg$$

Five principal components can be calculated from the current data set. Three conditions are used to find the coefficients ($a_{11,}$ a_{12} etc.): the sum of the constants squared must equal 1, the variance of each principal component is maximised and the principal components are not correlated.

The calculation of principal components relies on calculating the eigenvalues of the correlation matrix of the variables after they have been standardised, the eigenvalues being the variances of the principal components and the elements of the corresponding eigenvector are the coefficients (a_{11}, a_{12} etc.) (Manly 1994). As a result of standardisation the mean concentration of each nutrient = 0 and the variance = 1. Because there are five variables the total variance = 5.0. The SAS PRINCOMP procedure was used to carry out the analysis (SAS 1989).

6.3 Nutrient concentrations

Among the five macronutrients analysed foliar N concentrations were highest followed by K, Ca and Mg with P present in the lowest concentrations, approximately one tenth the concentration of N. The species effect was highly significant for all nutrients (Table 6.1). With the exception of K there were no species x microsite interactions. The aspect and position main effects were not significant, however, significant aspect x position interactions were identified. There were no significant three way interactions.

6.3.1 Species

Between species variation accounted for a greater proportion of total variation in concentration of all nutrients than any other factor, explaining 48%, 43%, 39%, 42% and 57% of the total variation of N, P, K, Ca and Mg, respectively. Species differences in foliar nutrient concentrations were significant for all nutrients (Table 6.1). With the exception of Mg the highest concentrations were generally found in the eastern blue gums, *E. botryoides* and *E. saligna*, which had very similar nutrient profiles. Foliar N concentration was 19.2 mg/g in *E. saligna*, higher than all other species apart from *E. botryoides.* The stringybark species had low foliar N concentrations but there were significant differences (P = 0.05) between species at the bottom, (*E. agglomerata*) and top (*E. muelleriana, E. pilularis*) of the range covered by this group. *E. microcorys* also had relatively low foliar N. Foliar P concentrations were again highest in the eastern blue gums (1.93 and 1.87 mg/g for *E. botryoides* and *E. saligna* respectively) being significantly higher than all other species except *E. obliqua*. Similarly a group of species with low foliar P levels comprised several stringybarks and *E. microcorys.*

Foliar K levels essentially fell into subgeneric groups. The *Monocalyptus* species had low foliar K, ranging from 5.7 mg/g (*E. pilularis*) to 6.5 mg/g (*E. baxteri*) while those of the *Symphyomyrtus* species ranged from 7.1 mg/g (*E. nitens*) to 8.9 mg/g (*E. botryoides*). There were no significant differences among the *Monocalyptus* species, however, among the *Symphyomyrtus* species *E. botryoides* and *E. saligna* had significantly higher foliar K than *E. nitens* and *E. microcorys.*

Foliar Ca concentrations in *E. saligna*, *E. cladocalyx* and *E. botryoides* (7.5, 7.5 and 6.8 mg/g respectively) were significantly higher than all other species while *E. baxteri*, *E. globoidea*, and *E. microcorys* (4.1, 4.4 and 4.7 mg/g respectively) had lower Ca levels than all other species, except *E. regnans* and *E. nitens.* Differences in Ca concentrations among remaining species were small and not significant.

Eucalyptus pilularis had higher foliar Mg levels (3.8 mg/g) than all other species except *E. saligna.* The lowest concentrations were found in four species, *E. baxteri*, *E. cladocalyx*, *E. microcorys* and *E. nitens* (2.3, 2.3, 2.1 and 2.1 mg/g respectively), significantly lower than all other species.

Table 6.1 Mean foliar macronutrient concentrations (mg/g DM) for 12 *Eucalyptus* species. **Symphyomyrtus* species.

	N	P	K	Ca	Mg	N:P
E. agglomerata	11.4	1.41	6.0	5.5	3.1	8.3
E. baxteri	12.2	1.47	6.5	4.1	2.3	8.4
E. botryoides*	17.8	1.93	8.9	6.8	3.0	9.4
E. cladocalyx*	15.5	1.51	8.1	7.5	2.3	10.3
E. globoidea	12.7	1.36	5.8	4.4	3.0	9.5
E. microcorys*	13.5	1.24	7.6	4.7	2.1	10.9
E. muelleriana	13.4	1.59	6.2	5.6	3.4	8.6
E. nitens*	14.7	1.38	7.1	5.4	2.1	10.7
E. obliqua	15.1	1.75	5.9	5.6	3.4	8.9
E. pilularis	13.0	1.34	5.7	5.5	3.8	9.9
E. regnans	16.6	1.59	6.4	4.9	2.9	10.6
E. saligna*	19.2	1.87	8.8	7.5	3.5	10.2
Significance	<0.00001	0.0006	0.0014	0.0008	<0.00001	0.01
CV (%)	12.1	16.1	15.9	7.4	13.7	12.7
lsd (P = 0.05)	1.43	0.20	0.90	0.79	0.32	1.0

There were significant (P = 0.01) species differences in the N:P ratio which ranged from 8.3 (*E. agglomerata*) to 10.9 (*E. microcorys*) but comprised three groups; N:P ratios <9, all *Monocalyptus* species, species between 9 and 10, and those >10. Four out of five species in the upper group were *Symphyomyrtus* species, the exception being *E. regnans*, whereas the other ash species, *E. obliqua,* fell into the lower group.

6.3.2 Aspect and slope position

The main effects of slope aspect and slope position did not significantly influence the foliar concentration of any nutrients (Table 6.2). They also contributed little to the total variation in nutrient concentrations, generally contributing less than 10% with the exception of slope position for N (13%) and Ca (27%). However there was a significant interaction between aspect and position for N ($P = 0.008$), K ($P = 0.007$), Ca ($P = 0.002$) and Mg ($P = 0.03$) (Figure 6.1). P concentrations were not influenced by slope position and although there appeared to be a small aspect effect this was not significant. For the remaining nutrients, there was a strong position effect on the shady face whereas on the sunny face the position effect was small. The concentration of N and K was lowest on the lower shady face. Conversely, concentrations of Ca and Mg were highest on the lower shady face.

There was also a significant ($P = 0.04$) aspect x position interaction on the N:P ratio, which was lower on the bottom shady microsite (8.3) than the upper shady microsite (10.7) whereas there was little difference between slope positions on the sunny face (10.0 and 9.3 for the upper and lower slope positions respectively). This is probably a reflection of the low N concentrations on the lower shady microsite.

Table 6.2 Effect of slope aspect and slope position on foliar macronutrient concentrations (mg/g DM) and the N:P ratio.

	N	P	K	Ca	Mg	N:P
Aspect						
Shady	14.4	1.51	6.6	5.4	2.8	9.7
Sunny	14.8	1.56	7.3	5.9	3.0	9.6
Significance	NS	NS	NS	NS	NS	NS
Position						
Upper	15.7	1.53	7.4	5.1	2.7	10.5
Lower	13.4	1.54	6.4	6.2	3.1	8.8
Significance	NS	NS	NS	NS	NS	NS

6.3.3 Species and slope position interaction for potassium

Apart from a significant ($P = 0.016$) interaction between species and slope position for K no other interactions involving species were found. The interaction of species and slope position on foliar K is shown in Table 6.3. Generally K concentrations were higher on the upper slope, the only exception being *E. muelleriana*, however, differences were significant in four species only, *E. baxteri*, *E. cladocalyx*, *E. nitens* and *E. obliqua*.

Table 6.3 The interaction between species and slope position on foliar potassium (K) concentrations (mg/g DM).

	Position		
	Upper	Lower	Difference
E. agglomerata	6.5	5.5	+1.0
E. baxteri	7.2	5.6	+1.6*
E. botryoides	9.2	8.7	+0.5
E. cladocalyx	9.0	7.2	+1.8*
E. globoidea	6.1	5.6	+0.5
E. microcorys	7.6	7.5	+0.1
E. muelleriana	6.1	6.5	-0.4
E. nitens	8.5	5.7	+1.8*
E. obliqua	6.9	4.9	+2.0*
E. pilularis	6.2	5.3	+0.9
E. regnans	6.6	6.2	+0.4
E. saligna	9.3	8.4	+0.9

* Significantly different ($P \leq 0.01$)

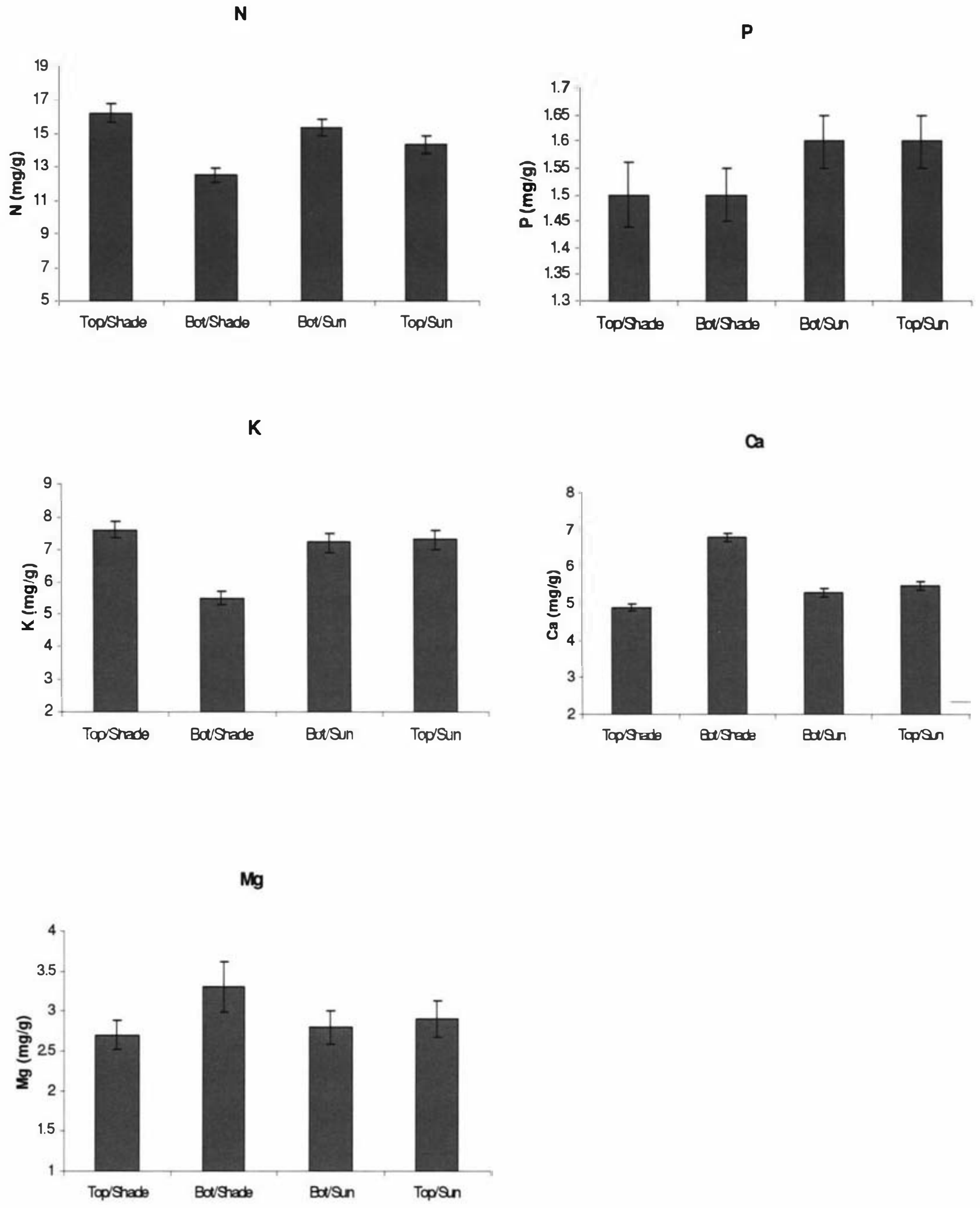


Figure 6.1 Interaction of slope aspect and slope position on foliar macronutrient concentrations (mg/g DM) at 30 months. Error bars = 2 x SEM.

6.4 Subgeneric contrasts

Subgeneric orthogonal contrasts reveal that the mean concentration of foliar nutrients in *Symphyomyrtus* species was significantly different from *Monocalyptus* species (Table 6.4). Concentrations of N, P, K and Ca were higher in *Symphyomyrtus* but lower for Mg. The N:P ratio was also higher in *Symphyomyrtus*, mostly because of higher N content. The difference in P content was relatively small (1.5 and 1.58 mg/g for *Monocalyptus* and *Symphyomyrtus* respectively) but was significant ($P = 0.05$). All other contrasts were highly significant ($P < 0.0001$).

Table 6.4 Contrasts of mean foliar macronutrient concentrations (mg/g DM) and nutrient ratios for *Monocalyptus* and *Symphyomyrtus* species. All contrasts are significant ($P = 0.05$ for P; $P < 0.0001$ for all remaining contrasts). Numbers in parentheses = SEM.

	Monocalyptus	Symphyomyrtus
N	13.48 (0.27)	16.13 (0.46)
P	1.50 (0.029)	1.58 (0.048)
K	6.08 (0.14)	8.10 (0.22)
Ca	5.09 (0.12)	6.38 (0.24)
Mg	3.13 (0.07)	2.61 (0.09)
N:P	9.17 (0.21)	10.30 (0.19)

6.5 Nutrient correlations

6.5.1 Species

Nitrogen was significantly positively correlated with P in *E. cladocalyx*, *E. nitens*, and *E. saligna* and was close to being significantly correlated in *E. botryoides* (P = 0.065) and *E. microcorys* (P = 0.076), all of which are *Symphyomyrtus* species (Table 6.5). Nitrogen was positively correlated with K in all species except *E. baxteri*, *E. globoidea*, *E. muelleriana*, and *E. pilularis*, all *Monocalyptus* species, while correlations between N and Ca, and, N and Mg were negative in all cases.

Apart from N, correlations between P and remaining nutrients were uncommon, the only instances being with K (*E. saligna)* and Mg (*E. obliqua)*. Potassium was negatively correlated with either Ca or Mg or both in most species, the exceptions being *E. botryoides* and *E. muelleriana*. The correlations between Ca and Mg were positive and occurred in all species apart from *E. botryoides*, *E. cladocalyx* and *E. saligna*.

6.5.2 Subgenus

The correlations between foliar nutrients of species amalgamated according to subgenus were also analysed (Table 6.6). Although most of the correlations in Table 6.6 are statistically significant, many are relatively weak and probably of limited biological significance. For example, in *Monocalyptus* only the correlations between K, Ca and Mg are of much interest, K being negatively correlated with Ca and Mg (r = -0.50 and -0.59 respectively) while the correlation between Ca and Mg was quite strong (r = 0.73). The correlations with N are all weak. In contrast, the N-P and N-K correlations in *Symphyomyrtus* are relatively strong (r = 0.77 and 0.76 respectively) while the correlation between K and Ca is weak and that between K and Mg, insignificant.

Table 6.5 Pearson correlation matrices for foliar macronutrient concentrations (mg/g DM) for each species. Correlations underlined are significant at P ≤0.05 and those in bold at P ≤0.01.

	N	P	K	Ca		N	P	K	Ca
E. agglomerata					E. baxteri				
P	-0.18					0.32			
K	**0.70**	-0.30				0.05	-0.19		
Ca	**-0.70**	0.29	-0.67			-0.06	0.03	-0.20	
Mg	-0.58	0.41	-0.46	**0.77**		0.21	0.43	**-0.72**	0.56
E. botryoides					E. cladocalyx				
P	0.55					**0.70**			
K	**0.74**	0.20				**0.77**	0.38		
Ca	-0.19	0.43	-0.3			**-0.74**	-0.16	-0.61	
Mg	-0.41	-0.29	-0.47	0.23		-0.46	-0.31	-0.62	0.46
E. globoidea					E. microcorys				
P	0.31					0.53			
K	0.31	-0.33				0.65	0.34		
Ca	-0.44	0.29	-0.53			**-0.76**	-0.37	**-0.76**	
Mg	-0.65	0.29	-0.65	**0.70**		-0.66	-0.35	-0.63	**0.82**
E. muelleriana					E. nitens				
P	-0.16					**0.74**			
K	0.50	0.13				**0.78**	0.43		
Ca	-0.52	0.46	-0.23			-0.43	0.10	**-0.75**	
Mg	-0.56	0.35	-0.38	**0.72**		**-0.72**	-0.30	**-0.91**	**0.81**
E. obliqua					E. pilularis				
P	-0.13					0.19			
K	**0.76**	-0.16				0.33	-0.26		
Ca	**-0.72**	0.57	**-0.79**			-0.34	0.44	**-0.78**	
Mg	-0.56	0.64	**-0.79**	**0.85**		-0.39	0.32	**-0.81**	**0.76**
E. regnans					E. saligna				
P	0.03					**0.88**			
K	**0.78**	-0.03				**0.85**	**0.72**		
Ca	**-0.86**	-0.09	**-0.76**			-0.58	-0.31	**-0.84**	
Mg	**-0.80**	0.31	**-0.85**	**0.80**		**-0.70**	-0.41	-0.66	0.57

Table 6.6 Pearson correlation matrices for foliar macronutrient concentrations (mg/g DM) in *Monocalyptus* and *Symphyomyrtus* subgenera. Correlations underlined are significant at P ≤0.02 and those in bold at P ≤0.0001.

	N	P	K	Ca	N	P	K	Ca
Monocalyptus					Symphyomyrtus			
P	0.25				**0.77**			
K	0.38	-0.07			**0.76**	**0.51**		
Ca	-0.30	0.33	**-0.50**		-0.06	0.34	-0.26	
Mg	-0.24	0.26	**-0.59**	**0.73**	0.24	0.46	-0.02	**0.60**

A scatterplot of P and N concentrations highlights the differences between the subgenera (Figure 6.2). The range in N concentrations in the *Monocalyptus* species is less than the *Symphyomyrtus* species and the association between N and P is noticeably weaker in *Monocalyptus*. Two points with high P values appear to be possible outliers. The analytical report was checked to ensure there had been no transcription errors and repeated analysis (6 times) of standard samples at regular intervals, which indicated little variation between repeated samples (CV's of 2.3%, 3.1%, 1.8%, 5.5% and 2.6% for N, P, K, Ca and Mg respectively), suggests that these results are not outliers. The scatterplot of the correlation between N and K for each subgenus reveals greater variation in the data for the *Monocalyptus* species (Figure 6.3). However, the scatterplot of Ca and Mg concentrations (Figure 6.4) shows greater Ca variation and concentration in *Symphyomyrtus*. Analyses of the subgeneric differences in nutrient correlations show that many of the correlations involving N and K were significantly different ($P < 0.01$). The correlations between N and P and N and K were significantly stronger in *Symphyomyrtus* than *Monocalyptus* whereas the correlation between N and Mg is relatively weak in both subgenera but is negative in *Monocalyptus* (Table 6.6). The correlation between K and P is moderately strong and highly significant in *Symphyomyrtus* but not significant in *Monocalyptus*. In contrast there was no correlation between K and Mg in *Symphyomyrtus* whereas there was a moderately strong correlation between these two nutrients in *Monocalyptus*.

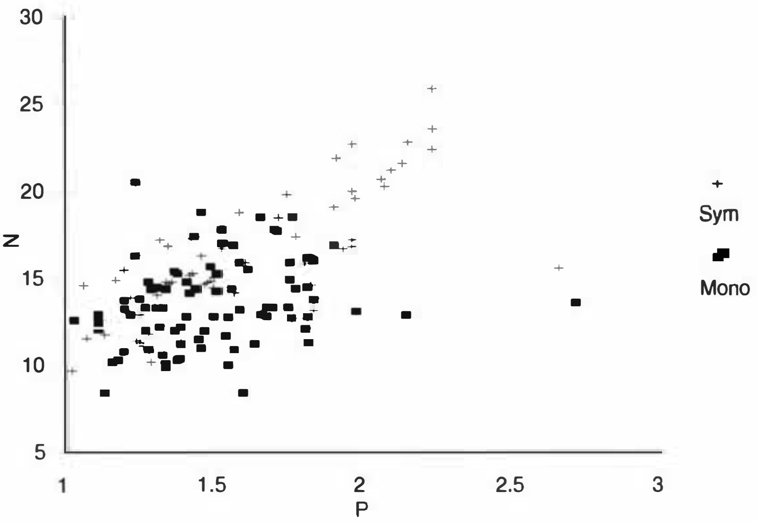


Figure 6.2 Scatterplot of mean foliar nitrogen (N) versus mean foliar phosphorus (P) concentrations (mg/g DM) in *Monocalyptus* and *Symphyomyrtus* species.

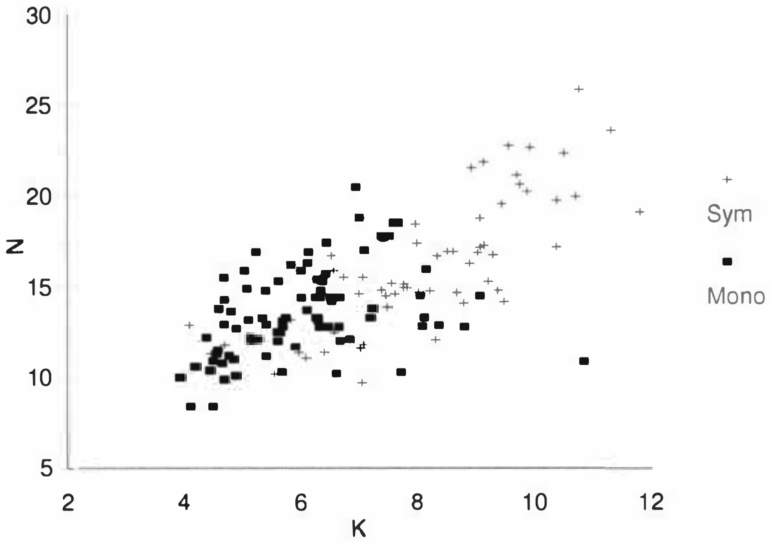


Figure 6.3 Scatterplot of mean foliar nitrogen (N) versus foliar potassium (K) concentrations (mg/g DM) in *Monocalyptus* and *Symphyomyrtus* species.

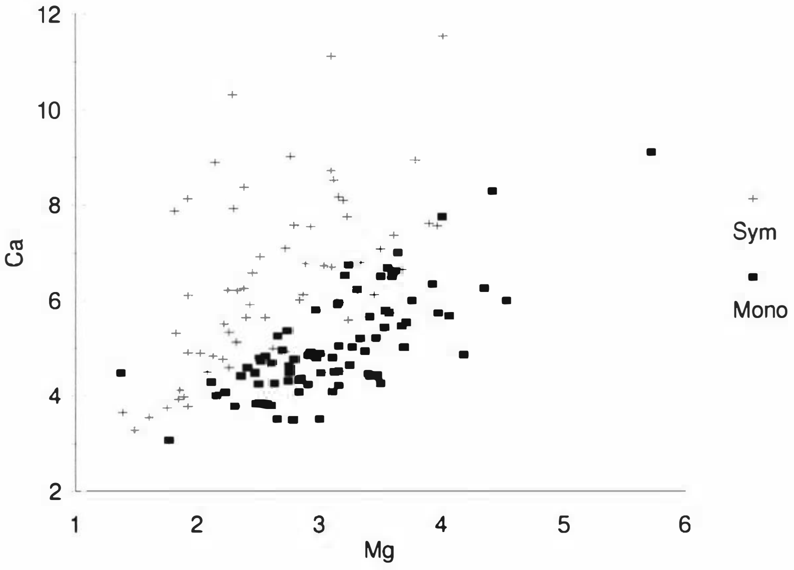


Figure 6.4 Scatterplot of mean foliar calcium (Ca) versus foliar magnesium (Mg) concentrations (mg/g DM) in *Monocalyptus* and *Symphyomyrtus* species.

6.5.3 Microsite

Separate correlation analysis was carried out for each microsite (Table 6.7) and revealed that correlations on the upper shady face were generally strong and highly significant. The exceptions were those correlations involving Mg. On the lower shady microsite the N-P and N-K correlations, though highly significant, were only moderately strong ($r = 0.64$ and $r = 0.62$ respectively). This was also the case on the lower sunny microsite. On the upper sunny microsite it was only the K-P and K-Mg correlations that are of any interest; $r = 0.53$ and $r = -0.51$ respectively, the remaining correlations being relatively weak or insignificant.

There were significant slope position differences in correlations from the upper slope, mostly those correlations involving P. The correlation coefficients for N-P, P-K and P-Ca ($P \leq 0.05$), N-Ca and P-Ca ($P \leq 0.01$) were significantly higher on the upper slope than the lower (Table 6.6). Many of the correlations from the upper shady microsite were also higher than those on the sunny aspect. On the upper sunny aspect the P-N, P-K, K-N, K-Mg ($P \leq 0.0001$), Ca-P and Ca-K ($P \leq 0.01$) correlations were lower than those for the upper shady microsite. On the lower sunny aspect the N-Ca, K-Mg ($P \leq 0.0001$), K-P, K-Ca ($P \leq 0.001$), P-N and P-Ca ($P \leq 0.05$) correlations were also lower than the upper shady microsite. Apart from K-Mg the nutrient correlations on the sunny aspect were greater than those from the shady. The K-Mg correlation was negative for both slope positions on the sunny aspect but weakly positive on the upper shady microsite. In contrast there were no slope position differences among the correlation coefficients on the sunny aspect.

Table 6.7 Pearson correlation matrices for foliar macronutrient concentrations (mg/g DM) for each microsite. Underlined correlations are significant at P ≤0.05 and those in bold at P ≤0.001. Microsite comparisons require correlations to differ by at least 0.52 for P ≤ 0.001, 0.39 for P ≤0.01 and by at least 0.27 for P ≤0.05. For example, the correlation between N and P on the upper shady microsite is r = 0.91 and on the lower shady microsite r = 0.64. The difference between these correlations is 0.27 so the correlations are significantly different (P ≤ 0.05).

	N	P	K	Ca		N	P	K	Ca
Upper shady					Lower shady				
P	**0.91**					**0.64**			
K	**0.77**	**0.73**				**0.62**	0.35		
Ca	**0.69**	**0.70**	**0.55**			0.27	0.37	0.35	
Mg	0.23	0.23	0.20	0.39		0.0	0.27	-0.22	0.23
Upper sunny					Lower sunny				
P	0.36					**0.55**			
K	**0.53**	0.04				**0.60**	0.21		
Ca	0.16	0.27	0.13			0.10	0.32	-0.10	
Mg	-0.13	0.40	**-0.51**	0.22		0.10	0.32	-0.37	0.43

6.6 Principal components analysis

The eigenvalues of the correlation matrix for the nutrient data are shown in Table 6.8. The first principal component has a variance of 2.080 and accounts for 41.6% (2.08/5) of the total variation in the data set. The second principal component is almost as important, having a variance of 1.728, explaining 34.6% of total variation. The first two principal components combined account for 76.2% of total variation. The third principal component accounts for a much smaller proportion of the variation (12.6%) with the remaining components being about of equal importance but together explaining only 11.2% of the total variation. The first three principal components account for almost 89% of total variation thus, allowing for parsimony, the original five variables can be adequately summarised by these three components (Afifi & Clark 1996).

The coefficients can be used to interpret each principal component. Large numerical coefficients have more influence than small. The first principal component appears to be a measure of N, P and K, the coefficients being 0.635, 0.465 and 0.586, respectively, while the coefficients for Ca and Mg are close to 0 (Table 6.9). This means that principal component 1 will be high in plots with a high concentration of N, P and K. Principal component 2 will be high when P, Ca and Mg concentrations are high and principal component 3 appears to mainly be a contrast between Ca and Mg and to a lesser extent, P. The coefficient for Ca is large and positive (0.791) whereas the coefficients for Mg and P are moderate and negative (-0.396 and -0.321 for Mg and P, respectively). This component will be high when Ca concentration is high and when Mg and P concentrations are low (for example, plot 37 in Appendix 7). The fourth component is primarily a contrast between P and Mg and the fifth a contrast between N and K.

Table 6.8 Eigenvalues of the correlation matrix.

	Eigenvalue	Difference	Proportion	Cumulative
1	2.080	0.352	0.416	0.416
2	1.728	1.097	0.346	0.762
3	0.632	0.295	0.126	0.888
4	0.336	0.113	0.067	0.955
5	0.223	-	0.045	1.000

Table 6.9 Eigenvectors of the principal components.

	Prin1	Prin2	Prin3	Prin4	Prin5
N	0.635	0.004	-0.219	0.285	-0.684
P	0.465	0.435	-0.321	-0.648	0.267
K	0.586	-0.252	0.257	0.380	0.619
Ca	0.089	0.580	0.791	-0.009	-0.171
Mg	-0.170	0.641	-0.396	0.595	0.221

Plotting principal components is useful for recognising and interpreting patterns in the data if the individual data points are coded. The first principal component plotted against the second component with each point numbered to indicate subgenera reveals that all *Monocalyptus* species occur below about 1.5 for principal component 1 whereas *Symphyomyrtus* species range up to about 5 for principal component 1

(Figure 6.5). Principal component 1 is a reflection of N, P and K content indicating that the concentration of these nutrients was lower in *Monocalyptus* species. Examination of Table 6.1 reveals that in general the *Monocalyptus* species had lower N, P and K contents than *Symphyomyrtus* species. There is little between the subgenera for principal component 2. When principal component 1 is plotted against principal component 3 (Figure 6.6), a clear distinction between subgenera is evident. All but one *Monocalyptus* plot occurs in the bottom left of the graph. *Monocalyptus* species have mostly scored lower for principal component 3 than *Symphyomyrtus*. This component contrasts Ca with Mg and P. Low principal component 3 scores associated with *Monocalyptus* species indicate that, typically, *Monocalyptus* have low Ca but with moderate P and high Mg content. Only one *Symphyomyrtus* plot attained a score of less than zero for both principal component 1 and 3 whereas many *Monocalyptus* plots were negative for both. The plot of principal component 2 against principal component 3 again highlights the distinction between subgenera for principal component 3 (Figure 6.7).

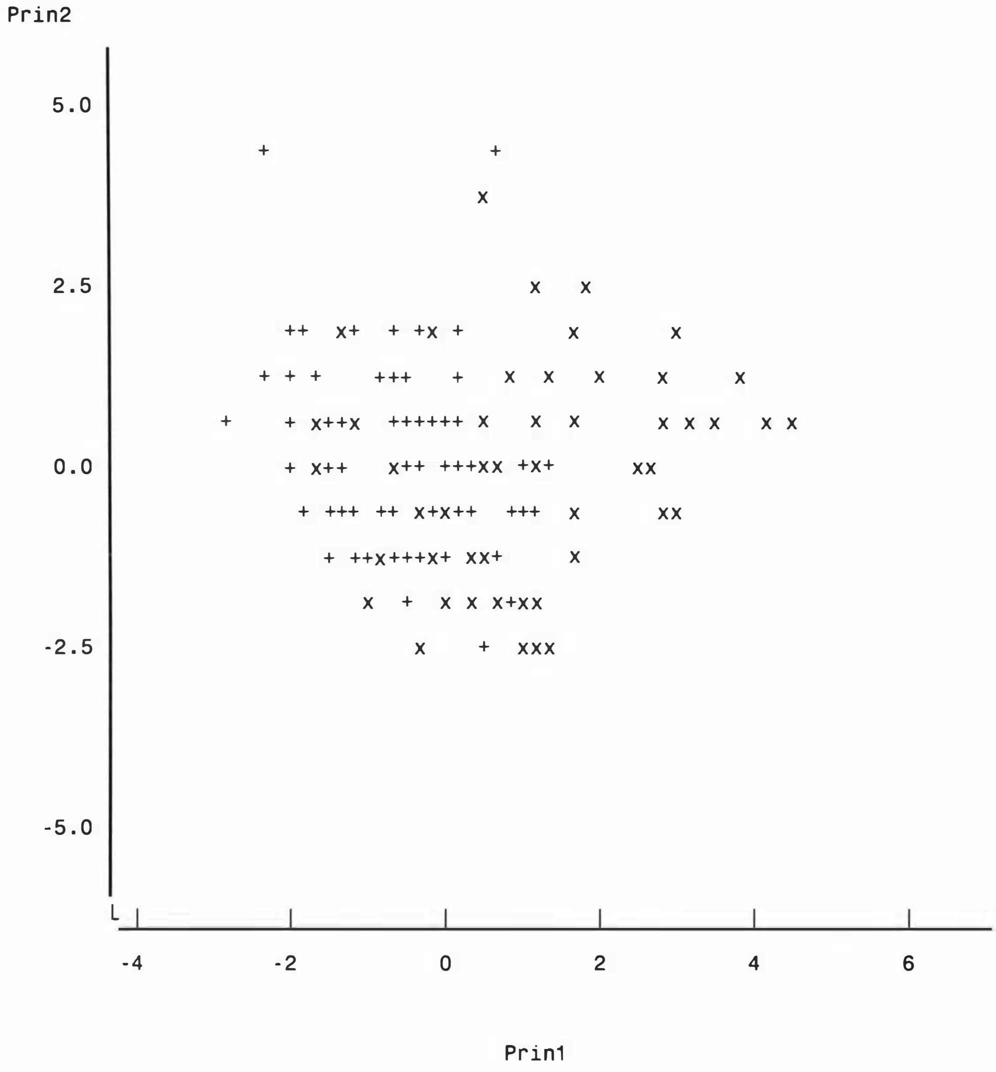


Figure 6.5 Plot of principal component 1 against principal component 2 for foliage nutrient data. + = *Monocalyptus*, x = *Symphyomyrtus*.

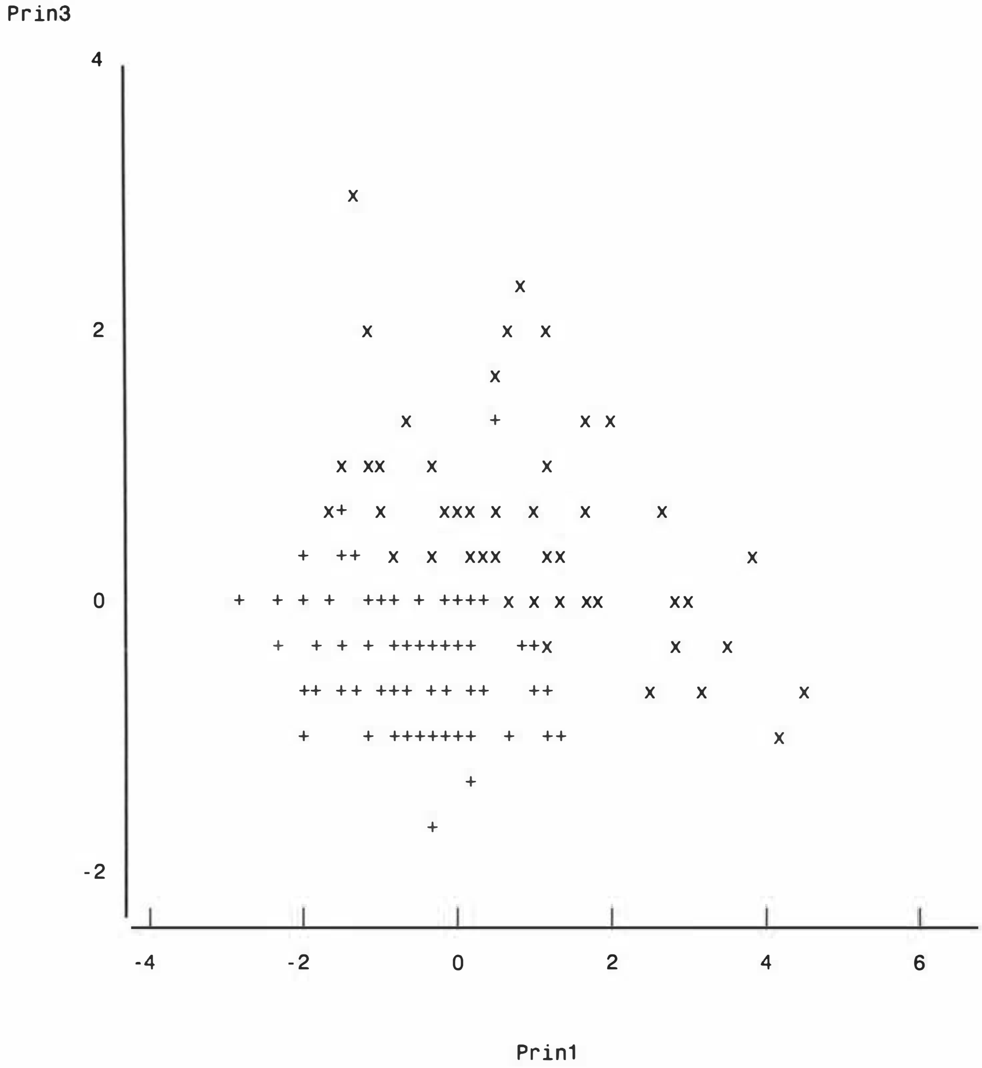


Figure 6.6 Plot of principal component 1against principal component 3 for foliage nutrient data. + = *Monocalyptus*, x = *Symphyomyrtus*.

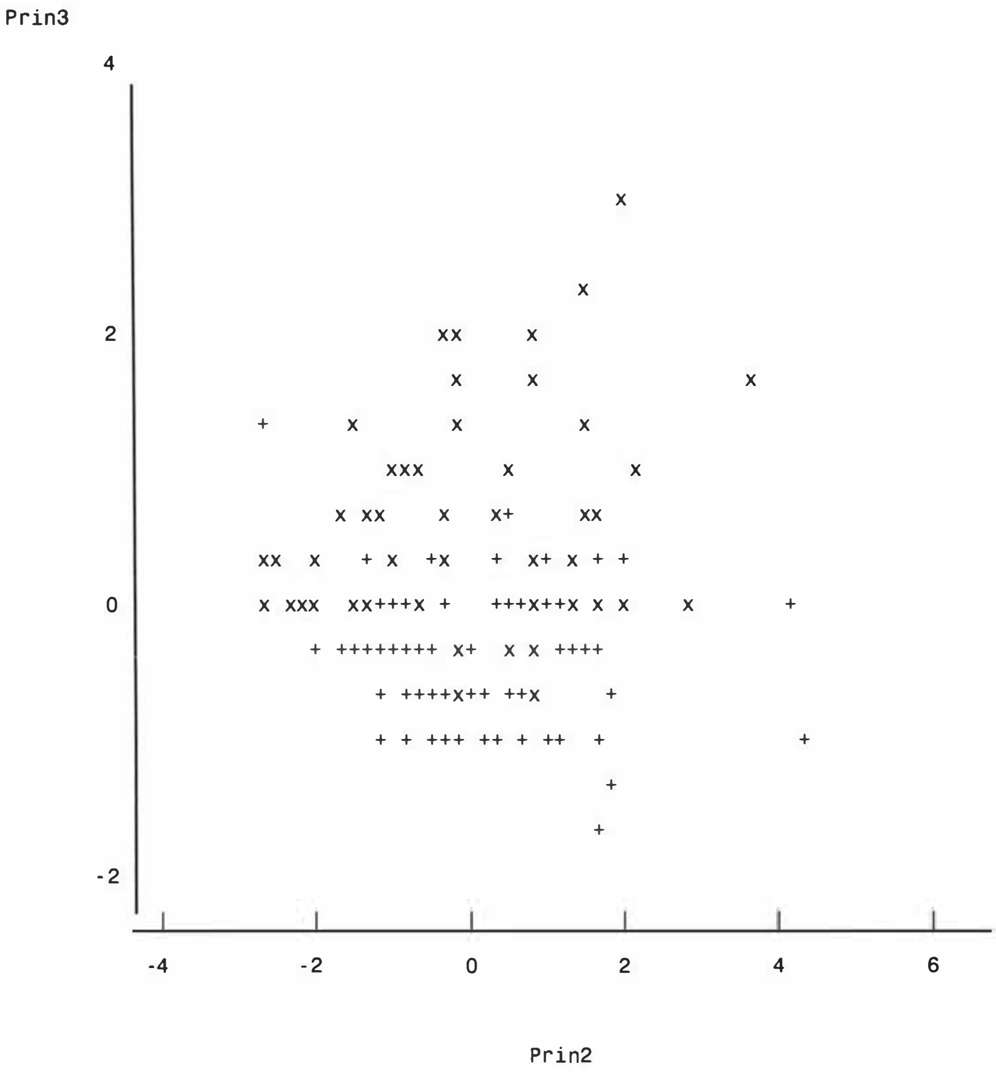


Figure 6.7 Plot of principal component 3 against principal component 2 for foliage nutrient data. + = *Monocalyptus*, x = *Symphyomyrtus*.

Figures 6.5, 6.6 and 6.7 highlight subgeneric differences in principal component scores for the first three principal components. The scores for principal components 1 and 3 are significantly different but there was no difference in principal component 2 (Table 6.10). The mean scores for the first principal component were -0.63 and 0.88 for *Monocalyptus* and *Symphyomyrtus* respectively. Similarly the mean scores for the third component were -0.4 and 0.56 respectively. This indicated, recalling the nutrient weights for each score (Table 6.9), that *Symphyomyrtus* species typically have higher foliar concentrations of N, P and K than *Monocalyptus* species and that *Monocalyptus* species have low Ca but with moderate P and high Mg whereas in *Symphyomyrtus* species Ca concentrations were generally high (Figure 6.4) while Mg concentrations were low.

Table 6.10 Mean subgenus scores for the first three principal components.

	Prin1	Prin2	Prin3
Monocalyptus	-0.63	0.07	-0.40
Symphyomyrtus	0.88	-0.10	0.56
Significance	<0.0001	NS	<0.0001

6.7 Discussion

6.7.1 Nutrient concentrations

Nutrient concentrations were significantly influenced by species and microsite factors. This section will discuss possible causes and significance of these differences. Possible differences in the nutritional requirements of *Symphyomyrtus* and *Monocalyptus* species will also be explored.

6.7.1.1 Species and subgenera

There were highly significant species differences in the concentration of all macronutrients in this study. Differences in foliar nutrient concentrations among *Eucalyptus* species growing in the same environment have been found by many researchers (Olsen & Bell 1990; Guo 1998; Hawkins & Polglase 2000). Concentrations of most nutrients were highest in the eastern bluegum species, *E. botryoides* and *E. saligna* and lowest in the stringybark species. The concentration of nutrients in plant species is influenced by the availability of nutrients in the local environment and also by interactions with genetic characteristics which are often related to the ecological niche of a species (Garten 1978).

Subgeneric contrasts showed that *Symphyomyrtus* species had higher foliar N, P, K and Ca concentrations than *Monocalyptus*. The ecological explanation for this is that for the higher rainfall regions of the south east of Australia the distribution of *Eucalyptus* species is associated with soil fertility (Beadle 1962; McColl 1969). These differences have been attributed to species differences in nutritional physiology and associated with subgenera, *Symphyomyrtus* species, which are more likely to be found in higher fertility soils, generally having higher foliar nutrient concentrations than *Monocalyptus,* which are more typically found on lower fertility soils (Noble 1989; Olsen & Bell 1990; Florence 1996). The ecological benefits of maintaining low nutrient concentrations, particularly N, on low fertility soils may be due to the effects of low nutrient concentrations on herbivory (Cornelissen et al 1997; Alonso & Herrera 2003). Low leaf N in eucalypts has been shown to reduce diversity (Stone et al 1998), feeding (Marsh & Adams 1995) and growth (Fox & Macauley 1997) of insects as well as marsupial feeding activity (McArthur et al 2003).

However Judd et al (1996a), after reviewing published and unpublished data, found limited evidence to support claims of subgeneric differences in foliar N and P concentrations but did find evidence that concentrations of K, Ca and Mg are higher in *Symphyomyrtus.* In the current study there were significant differences in nutrient concentrations between species within each subgenus (Table 6.1). For example in *Monocalyptus*, the ash species *E. regnans*, has significantly higher N than any other *Monocalyptus* species. Similarly *E. obliqua* has significantly higher P than all of the stringybark species apart from *E. muelleriana.* There were also significant differences between *Symphyomyrtus* species for all nutrients. Further stratification of the Tuapaka data to facilitate contrasts between the ash species and the stringybarks within *Monocalyptus* and the ash species with the *Symphyomyrtus* species reveals that the mean foliar N and P content for the ash species do not differ from the means for the *Symphyomyrtus* species whereas the ash species have significantly higher N and P content than the stringybark species (Table 6.11). Conversely there is no difference between the ashes and the stringybarks for K, Ca and Mg whereas compared to the *Symphyomyrtus* species the ashes have significantly lower K and Ca but higher Mg. This indicates that any conclusion about the nutritional characteristics of *Monocalyptus* and *Symphyomyrtus* is likely to be influenced by the mix of species representing each subgenus.

Table 6.11 Contrasts between the ash and stringybark species and between the ash and *Symphyomyrtus* species for foliar macronutrient concentration (mg/g DM).

	N	P	K	Ca	Mg
Ash species	15.9	1.67	6.2	5.3	3.2
Stringybarks	12.5	1.43	6.0	5.0	3.1
Significance	<0.0001	0.0002	NS	NS	NS
Symphyomyrtus	16.1	1.59	8.1	6.4	2.6
Significance	NS	NS	<0.0001	<0.0001	<0.0001

Principal component analysis of foliage nutrient concentrations allowed the information on the concentration of five inter correlated nutrients to be adequately summarised by three uncorrelated principal components (Manley 1986). The components were characterised by the contribution of those nutrients correlated with each principal component to plant physiological processes. For example, principal component 3 was correlated with Ca and Mg which are both important in the structure of plant cells (Garten 1978). In this study principal component1, which was correlated with N, P and K, important in many plant cell metabolic functions and principal component 3 were useful for characterising subgenera. The mean score for both principal components was significantly higher in *Symphyomyrtus* than *Monocalyptus* and in only one case did a *Symphyomyrtus* species score less than 0 for both components. This indicated that, for the species utilised in this study, *Symphyomyrtus* tended to have higher concentrations of N, P and K as well as high Ca and/or low Mg.

The relationships between nutrient concentrations and indices of growth such as DBH and height can also be clarified by using principal component scores rather than nutrient concentrations themselves (Afifi & Clark 1996; Manly 1994). The principal components identified in Chapter 6 will be utilised in Chapter 7 to investigate the relationship between tree performance traits, such as stem volume at age 5 years and nutrient concentrations. Principal component analysis is also able to be used to examine the relationships between foliage nutrients and site factors such as soil and climate (Schleppi et al 2000). The influence of microsite factors on the relationships between foliage nutrients was investigated using principal component analysis in the current study but failed to provide any insight (data not shown). This is not surprising given that variation in foliage nutrient concentration due to microsite was relatively small.

Tree foliage nutrient concentrations can be compared to 'norms' which provide a guide for making judgements about the adequacy of nutrient supply. The potential benefits of applying fertilisers can then be estimated. For example, there are published standards for *Pinus radiata* in New Zealand which allocate foliage nutrient concentrations into categories (low, marginal and satisfactory) as well as a broad recommendation for eucalypts that foliar N concentration should be > 2.0% and that P concentrations should be > 0.15% (Will 1985). The probability of an economic response to application of a fertiliser is high when nutrient concentrations are low and decline as nutrient concentrations increase. There is little information on normal or recommended nutrient concentrations for eucalypts (Dell et al1995) however Knight and Nicholas (1996) published provisional New Zealand norms for eucalypts between two and three years of age for three species; *E. delegatensis*, *E. regnans* and *E. saligna* (Table 6.12). These norms are based on the mean concentration of nutrients from good stands encountered during a nation wide survey; good stands were those with greater productivity than the national mean for that species. The N norms for *E. regnans* and *E. saligna* (1.93 and 2.07% of the DM respectively) are greater than those measured at Tuapaka (1.66 and 1.92% respectively). However, P concentrations at Tuapaka (Table 6.1) were greater than the norms provided by Knight & Nicholas (1996) while concentrations of K, Ca and Mg at Tuapaka were generally slightly higher than these norms (Table 6.12). Critical nutrient concentrations and nutrient concentrations categorised as normal or deficient have been published for a very limited number of species overseas, principally *E. grandis* (Herbert 1996; Huoran & Wenlong 1996). The critical concentration is defined as that necessary to achieve 90% of the maximum yield (Dell 1996). However, it is necessary to exercise care when interpreting such information because of the dependence of sampling position (Olsen & Bell 1990), season (Schönau 1981) and age of foliage (Lamb 1976) on nutrient concentrations, necessitating strict adherence to a standardised sampling procedure (Dell et al 1995).

Nutrient ratios have been promoted as being useful indicators of the nutritional status of eucalypts, particularly the N:P ratio (Herbert 1990; Herbert 1996). Optimum N:P ratios for several species have been suggested. For example, Judd et al (1996b), after surveying 26 plantations in Tasmania and Victoria, proposed that the critical N:P ratio for diameter growth in *E. nitens* was 15. This is very similar to ratios suggested for other species including *E. pilularis* (Cromer et al 1981). The N:P ratios achieved at Tuapaka were well below these levels, being 10.7 and 9.9 for *E. nitens* and *E. pilularis*, respectively (Table 6.1), and suggest that N may have been limiting, given that the P norms, for those species for which norms are available, indicate that P concentrations were adequate rather than high. The N:P ratios calculated from the nutrient norms in Table 6.12 also suggest that N may be limiting, being 14.0 and 14.6 for *E. regnans* and *E. saligna* respectively, well above the ratios achieved at Tuapaka. While nutrient ratios can provide useful information on nutrient balance status in eucalypts, it is important to maintain adequate concentrations of key nutrients (Dell et al 1995).

Table 6.12 Provisional norms for foliar macronutrient concentrations (% DM) for *E. regnans* and *E. saligna* in New Zealand. Adapted from Knight and Nicholas (1996).

	N	P	K	Ca	Mg
E. regnans	1.93	0.138	0.674	0.436	0.237
E. saligna	2.09	0.143	0.808	0.694	0.272

6.7.1.2 Microsite

Variation in foliar nutrient concentrations due to microsite was much less than that of species. This was probably a reflection of the nutrient status of the soil on each microsite, (Chapter 3). Soil nutrient levels were similar on all microsites and with the exception of P, which was quite high, were reasonably typical for Halcombe hill and Halcombe steepland soils (Cowie 1978). However, there were significant microsite interactions for all nutrients apart from P (Figure 6.1). All interactions involved the lower shady microsite which had lower N and K but higher Ca and Mg concentrations than the other microsites. Lower foliar concentrations of N and K probably reflect lower availability in the soil (Grove 1990; Olsen & Bell 1990).

Total soil N content is generally associated with the organic matter component (Stevenson 1982), which was generally high on all microsites. The proportion of N in the organic matter (C:N ratio) is unlikely to have been significantly lower on the lower shady microsite (McIntosh et al 1981; Lambert et al 2000; Blennerhassett 2002). However, the mineral N content of soil in hill country can vary widely due to factors such as pasture legume content, aspect and livestock grazing habits. Soil temperatures are generally lower on shady faces than on sunny in all seasons because of lower radiation inputs (Lambert et al 1977; Radcliffe & Lefever 1981) and this may reduce N mineralisation due to reduced microbial activity. Livestock prefer to camp on areas of gentle topography, such as ridges, resulting in fertility transfer as proportionately more dung and urine are returned to these localised camping sites (White 1990). This results in the transfer of nutrients, particularly N, P and K, away from steep areas to stock camps. Livestock also spend more time on sunny faces rather than shady (Scott 1973) increasing the probability of nutrient transfer from shady faces. Average slope gradient and soil C content for each microsite is shown in Table 6.13. Soil C content was lowest on the upper sunny and lower shady microsites, the microsites with the steepest slope gradients.

The low foliar K content on the lower shady microsite is also likely to be a reflection of the low soil K levels on this microsite and probably also the result of fertility transfer by livestock (White 1990). In contrast, foliar Ca and Mg levels on the lower microsite are higher than on other microsites despite the fact that microsite differences in soil test values for these nutrients were minor. (Chapter 3). This is likely to be a consequence of low soil K levels on the lower shady microsite. K^+ is the most important cation for counteracting anions, particularly NO_3^-, during transport and storage and is also important for regulating osmotic function. If the availability of K^+ is low the uptake of both Ca^{2+} and Mg^+ cations may increase in order to preserve ionic balance (Dell et al 1995; Marschner 2002).

There have been few studies of the effects of microsite on the nutritional status of eucalypts in New Zealand, however, Bathgate et al (1993) did find differences in foliar P concentrations on different microsites in a stand of *E. regnans* growing on the Volcanic Plateau near Tokoroa. Microsite differences were due to variations in the thickness of Taupo tephra, which had a low P content, overlaying earlier deposits of Tirau tephra. Where the Taupo layer was shallow foliar P concentrations were higher, presumably because trees were better able to access P present in the Tirau soil.

Table 6.13 Slope angles (°) and % carbon (C) in the soil (15 cm depth) for each microsite.

	Slope	C
Upper shady	26.3	8.2
Lower shady	32.6	5.8
Upper sunny	30.8	5.4
Lower sunny	23.6	7.0

6.7.2 Nutrient correlations

Nutrient correlations were found in all species. Many studies have previously reported correlations between nutrient pairs in a wide range of plant species (Garten 1976; Cornelissen et al 1997; Alonso & Herrera 2001). Given that some nutrients are closely associated, for example Ca and Mg in plant structural tissues and N and P in plant biochemical systems (Dell et al 1996), their concentrations in plant tissue could be expected to be correlated. There were significant species differences in nutrient correlations, in particular N-P, N-K, and Ca-Mg correlations differed markedly. A number of factors have the potential to influence the concentration of nutrients in foliage, such as low or high concentrations in the soil leading to restricted or luxury consumption respectively (Garten 1976), thus influencing the correlation of plant nutrient concentrations. In the Tuapaka study for example, there were no significant N-P correlations among *Monocalyptus* species. This may be because *Monocalyptus* species have a greater ability to accumulate P than to accumulate N (Mulligan & Sands 1988; Hawkins & Polglase 2000). A number of studies have found that *Monocalyptus* species are more likely to be found on low fertility soils compared to *Symphyomyrtus*, consequently they are better adapted to low nutrient availability, particularly P, the improved ability to accumulate P giving them an ecological advantage on many sites in eastern Australia where soil P levels are low (Beadle 1962; Lambert & Turner 1983; Noble 1989; Harrington & Humphreys 2004).

6.8 Summary

There were significant species differences in the foliar concentration of all macronutrients included in this study, the eastern blue gums generally having high concentrations of all nutrients while the stringybarks were typically low, particularly for N and K. Subgeneric contrasts showed that the *Symphyomyrtus* species had higher concentrations of N, P, K and Ca but lower Mg than *Monocalyptus*. However, comparisons of individual groups within subgenera revealed that conclusions about the nutritional physiology of different subgenera are likely to be influenced by the balance of representative species. Microsite had less influence on nutrient concentrations than did species though there was a significant interaction between slope aspect and position for all nutrients except P, concentrations on the lower shady slope being lowest for N and K but highest for Ca and Mg. Comparison of nutrient concentrations measured at Tuapaka with critical or normal concentrations published for some species in New Zealand suggests that N concentrations were sub-optimal but that those of remaining nutrients were adequate. The low N:P ratios achieved at Tuapaka add weight to this suggestion.

Nutrient concentrations were often inter-correlated. N was strongly positively correlated with P and K in most *Symphyomyrtus* species but there were no significant correlations between N and P in *Monocalyptus*. Mg was strongly positively correlated with Ca but negatively correlated with K in most species. As a consequence Ca was usually negatively correlated with K. There was a small microsite influence on nutrient correlations, the most notable being that correlations on the upper shady face were significantly stronger than those on the other microsites which, apart from N-P correlations, were either weak or not significant. Principal component analysis was used to examine the nutrient profiles of different species. This analysis resulted in the generation of three uncorrelated principal components, which explained nearly 90% of the total variation in foliar nutrient concentrations and which were able to discriminate between subgenera.

Chapter 7

Growth, Stem Form, Wood Density and Tree Health

7.1 Introduction

The effects of aspect and slope position on the performance of 12 eucalypt species will be detailed. Performance will include survival, height, DBH, the ratio of DBH to height and stem volume at age 5 years as well as seasonal height (2 years) and diameter (1 year) growth between 2 and 4 years of age. The relationship between DBH and height and the influence of species and microsite on this relationship at age five years is also outlined. Additional aspects of performance include stem form, based on subjective scores at age 5 years and the acceptability of individual trees as potential crop trees based on the stem form criteria detailed in Chapter 3. The influence of microclimate and species on basic wood density measured at age 5 years will be reported. In addition, basic wood density measurements made from more mature trees at two sites in the Wairarapa, of the same species under evaluation at Tuapaka, will be presented. Relationships between wood density at Tuapaka and the Wairarapa sites will be examined.

The incidence and severity of pests and diseases and the effect these may have had on tree growth and stem form will also be outlined and, for more prevalent pest and disease problems found in *E. botryoides* and *E. saligna*, analysis of species and microsite differences. The relationships between the incidence of pests and growth and form in these species will also be explored with the aid of logistic regression. An investigation of the root structure, including radial distribution and size distribution of lateral roots, was carried out on trees from two species and two microsites at age 6 years. The results from this work will also be presented here. Relationships between environmental characteristics, for example, nutrient concentrations, slope angle, exposure and growth and form will be explored, using both simple correlation and canonical correlation.

7.2 Seasonal growth

Seasonal height growth was measured over two years beginning September 1997 and finishing in September 1999. Diameter growth was also measured during this time, but many trees, particularly those from the slower growing species, were too small to allow measurement of diameter at breast height (DBH) during the first year (1997/98), consequently only the results from the second year (1998/99) of diameter measurements will be presented. Seasons were defined by three month periods as follows: Spring: September - November; summer: December - February; autumn: March - May; winter: June - August. Height and DBH (when possible) of all trees were measured at the beginning and end of each quarter. Relative seasonal growth was calculated but the growth pattern was similar to absolute growth for both diameter and height. Figures showing relative growth are provided in Appendix 8. Figures detailing the interaction between species, season, and year on height growth are also presented in the appendices (Appendix 9) rather than here because much of the information presented is similar to that in Figure 7.3 (species, season and aspect interaction).

Plot means for height and DBH were subject to repeated measures analysis of variance (ANOVA) using the 'repeated' facility of PROC GLM in SAS. Repeated measures ANOVA was required because repeated measurements over time on the same experimental units almost invariably results in correlation, in this case, for example, between growth traits in successive seasons. Repeated measures ANOVA takes into account this correlation allowing valid comparisons of effects over time: Year and season for height and season for DBH. (Steel & Torrie 1980). Significance tests were based on multivariate analysis of variance (MANOVA) test criteria including Wilks' Lamda, Pillai's Trace, Hotelling-Lawley Trace and Roy's Greatest Root. With a single exception, these tests produced the same probability value, that being a case in which Roy's Greatest Root differed from the others but to a minor extent.

7.2.1 DBH

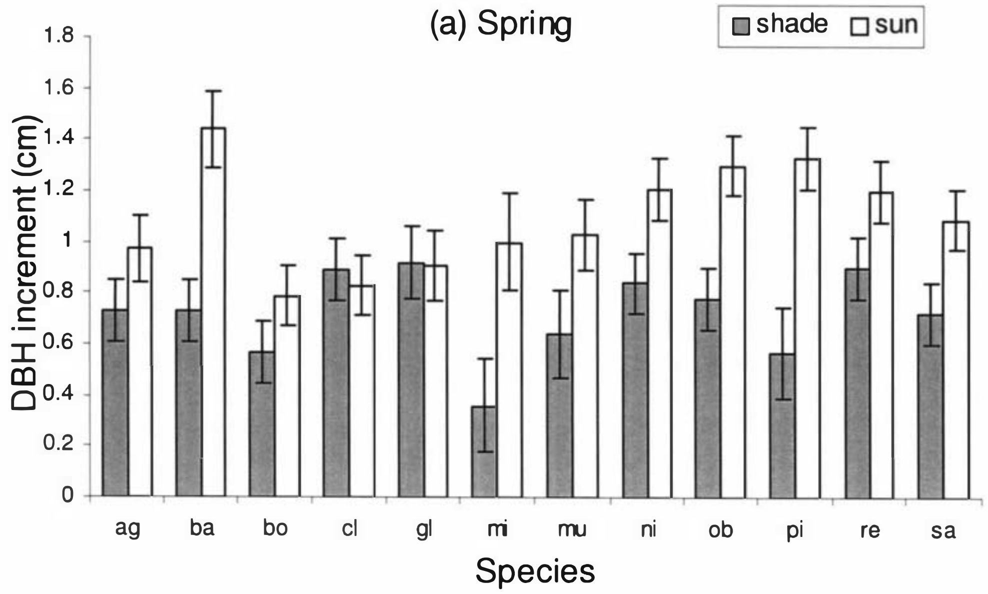
Mean seasonal diameter increments differed significantly ($P < 0.001$) being greatest in the spring (0.91 cm) and lowest in winter (0.38 cm) while summer (0.78 cm) and autumn (0.67 cm) were intermediate (Table 7.1). There was a significant interaction ($P = 0.05$) between season and slope position (Table 7.1). In autumn and winter diameter growth was significantly greater on the upper slope whereas in spring and summer there was little difference between slope positions.

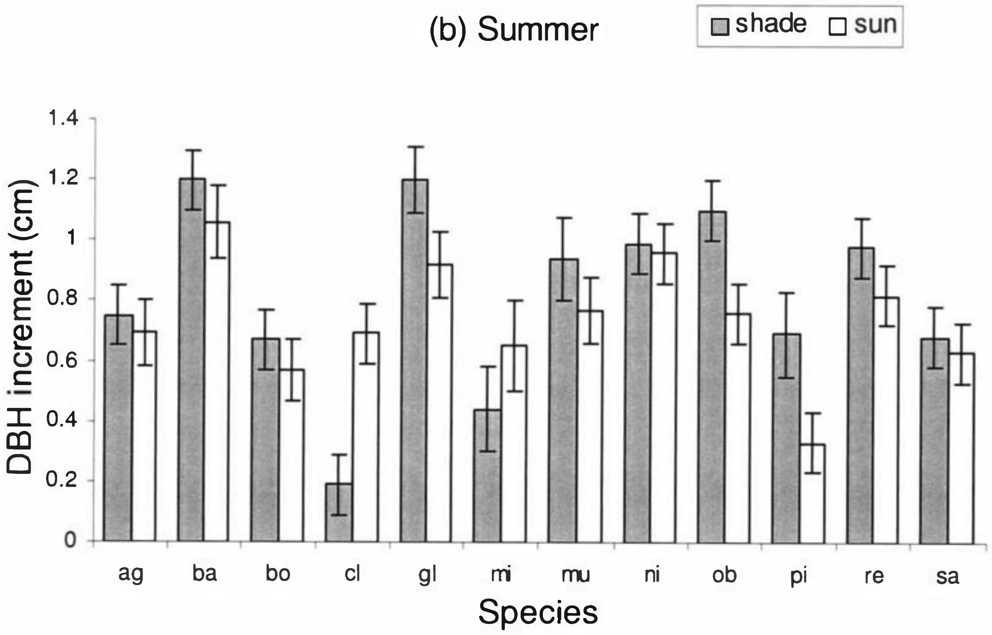
Table 7.1 The interaction between season and slope position on seasonal DBH increment (cm) in year 1998/99.

	Spring		Summer		Autumn		Winter	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
DBH	0.94	0.87	0.77	0.79	0.73	0.61	0.44	0.32
SEM	0.038	0.042	0.031	0.033	0.033	0.037	0.020	0.022

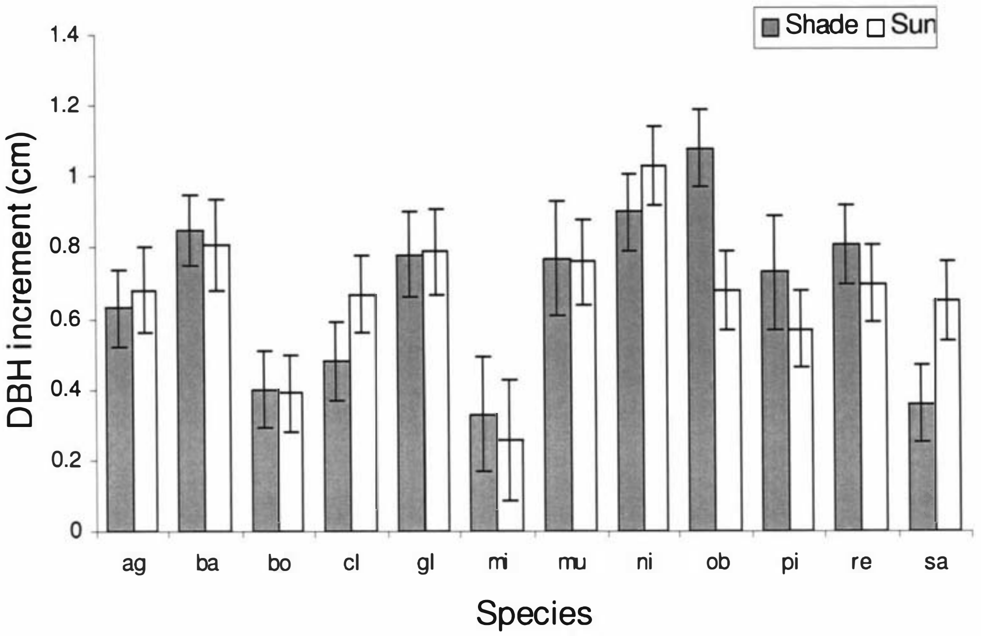
Additional significant two way interactions include season by species ($P < 0.001$) and season by aspect ($P < 0.001$). There was also a significant three-way interaction ($P = 0.02$) between season, aspect and species (Figure 7.1). Spring diameter growth was significantly higher on the sunny face for most species. The exceptions were *E. agglomerata*, *E. botryoides*, *E. cladocalyx* and *E. globoidea*. Aspect effects on the growth of individual species were greatest in *E. baxteri* and *E. pilularis*, which had better diameter growth than most other species on the sunny face but were similar to most species on the shady face. In contrast, aspect effects on diameter growth in the summer were not apparent in most species. Three species experienced better diameter growth on the shady face (*E. globoidea*, *E. obliqua* and *E. pilularis*) while *E. cladocalyx* was better (> 300%) on the sunny face, diameter growth in this species on the shady face being less than half that of the second poorest performing species on the shady face, *E. microcorys*. *E. pilularis* had the poorest performance on the sunny face. In autumn the aspect effects were again mostly not significant, the exceptions being *E. obliqua*, which was better on the shady face, and *E. saligna*, which was better on the sunny face. *E. microcorys* was the poorest species on both aspects. Aspect effects in the winter were similar to those in the spring. Apart from *E. obliqua*, all species had greater diameter growth on the sunny face. There was less variation in diameter growth during winter on the sunny face than the shady and there were few significant species differences whereas on the shady face there were many significant species differences. The poorest species on the shady face were *E. microcorys* and *E. regnans*.

Comparison of the effect of aspect on the proportional contribution of growth in each season to annual diameter growth reveals that in most species aspect differences were minor (Figure 7.2). In general the winter and spring seasons contributed less on the shady face compared with the sunny. This was most noticeable in *E. microcorys* and *E. regnans*, species with contrasting climatic adaptability. Conversely, the summer and autumn seasons were more important on the shady face than the sunny. However, in *E. cladocalyx* the contribution of summer growth to the annual growth in diameter on the shady face was relatively poor while spring was the most important season, contributing 45% of total annual diameter growth. On the sunny face *E. pilularis* also showed proportionately less summer and more spring growth while *E. microcorys* showed less autumn and more spring growth.


(a) Spring
▨ shade ☐ sun
DBH increment (cm)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species


(b) Summer
▨ shade ☐ sun
DBH increment (cm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species

(c) Autumn



(d) Winter

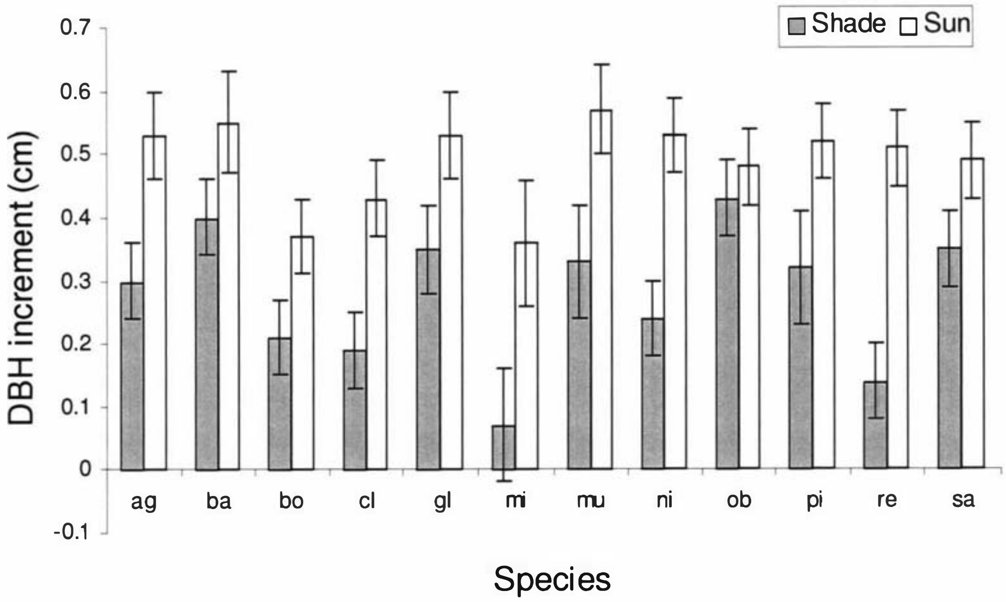


Figure 7.1 The interaction between species, aspect and season on DBH increment (cm) during (a) spring, (b) summer, (c) autumn and (d) winter between September 1998 and August 1999. Error bars = 2 x SEM.

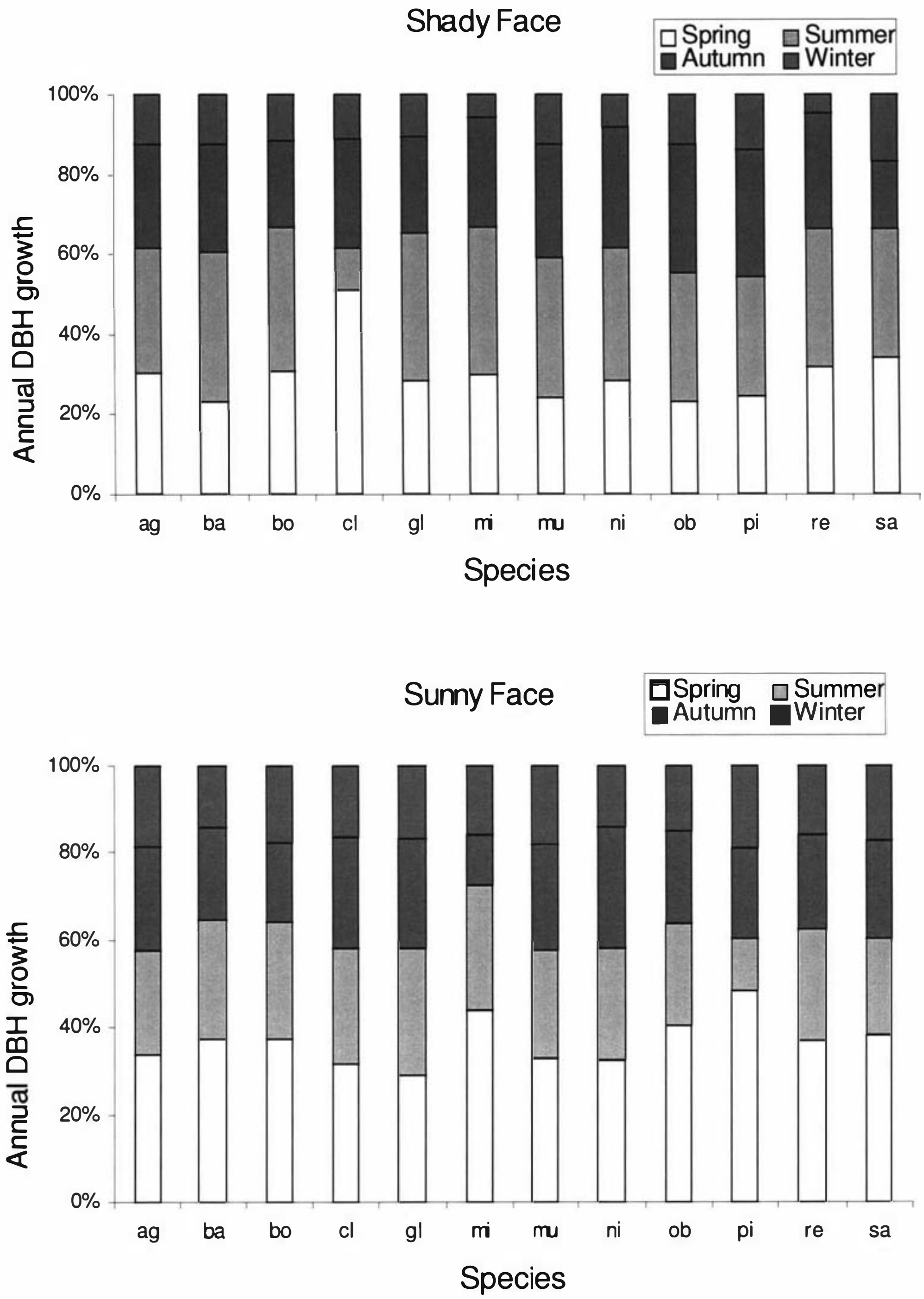


Figure 7.2 Proportional seasonal contribution (%) to annual DBH growth for each aspect between September 1998 and August 1999.

7.2.2 Height

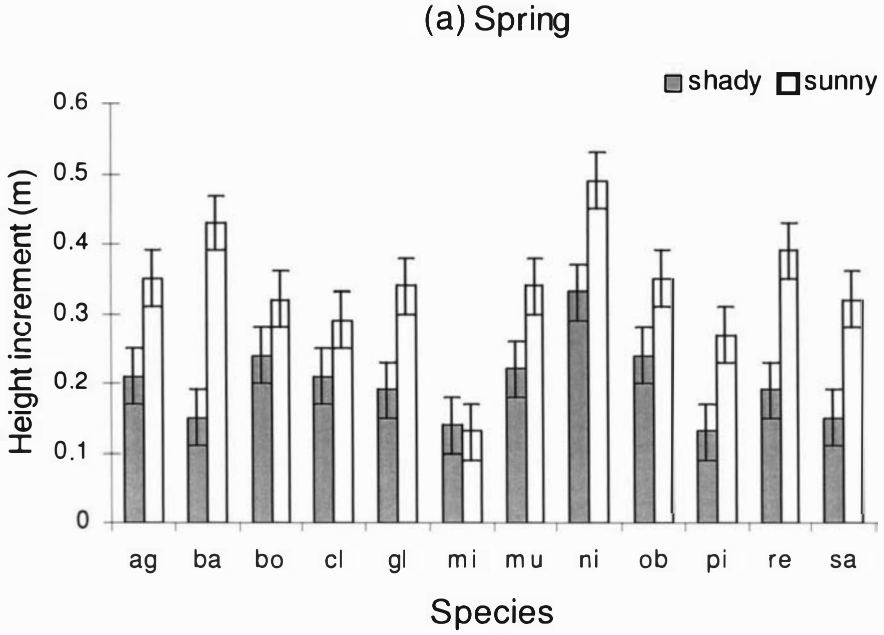
Mean height growth was strongly influenced by season ($P < 0.0001$) being highest over the summer, contributing more than 50% of annual height growth, in both years and least during winter, while spring and autumn growth increments were intermediate (Table 7.2). There was a significant season x year interaction ($P = 0.001$) on mean height growth; 1997/98 being better than 1998/99 during the summer (0.60 and 0.53 m for year 1997/98 and 1998/99 respectively) but there was little or no difference in the remaining seasons (Table 7.2). There was no interaction between species and year.

There was a significant ($P = 0.01$) interaction between species, aspect and season on mean height growth. During the spring height growth was better on the sunny face in all species apart from *E. microcorys* (Figure 7.3a). In three species (*E. baxteri*, *E. regnans* and *E. saligna*) height growth on the sunny aspect was more than double that of the shady aspect. Height growth over the summer was also higher on the sunny aspect in most species (Figure 7.3b) but the advantage was less than in the spring and in several species there were no aspect differences (*E. agglomerata*, *E. baxteri*, *E. globoidea* and *E. obliqua*). During the autumn height growth was again better on the sunny face but only in *E. cladocalyx*, *E. globoidea*, *E. microcorys*, *E. muelleriana* and *E. nitens* were differences large, height growth being at least twice that of the shady face. In contrast, height growth during the autumn was better on the shady face in *E. saligna* (Figure 7.3c). Height growth over the winter was again better on the sunny face in most species, differences being minimal in *E. globoidea*, *E. microcorys*, *E. regnans* and *E. saligna*. In *E. agglomerata* and *E. baxteri* winter height growth was close to zero on the shady face, however in *E. botryoides* height growth was close to zero on both aspects (Figure 7.3d). *E. nitens* was either the best or among the best species on both aspects during the spring, summer and autumn. However, in the winter *E. cladocalyx* was the best species on both aspects.

There was a significant ($P = 0.0014$) four way interaction between season, aspect, slope position and year on height growth. During the spring height growth was greater in 1998/99 apart from the upper shady aspect which was considerably better in 1997/98 (Figure 7.4a). During summer height growth differences were small or insignificant on the shady face whereas on the sunny face growth was significantly higher in 1997/98 (Figure 7.4b). Autumn height growth on different microsites was similar to the summer (Figure 7.4c), but whereas in summer there was no difference in growth between microsites in 1998/99, growth during the autumn on the upper sunny face in 1998/99 was significantly higher than on the other microsites. Height growth was least in the winter on all microsites and the pattern of growth was similar to that seen in the spring, growth on the sunny face being better in 1998/99 whereas on the upper shady face growth was better in 1997/98 (Figure 7.4d). Winter growth on the lower shady face was poor in both years.

Table 7.2 Effect of season and year on seasonal height growth (m). Year 1 = 1997/98, year 2 = 1998/99.

	Spring		Summer		Autumn		Winter	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Height	0.26	0.28	0.60	0.53	0.19	0.16	0.09	0.09
SEM	0.01	0.016	0.024	0.02	0.011	0.013	0.01	0.01


(a) Spring
shady
sunny
Height increment (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
ag
ba
bo
cl
gl
mi
mu
ni
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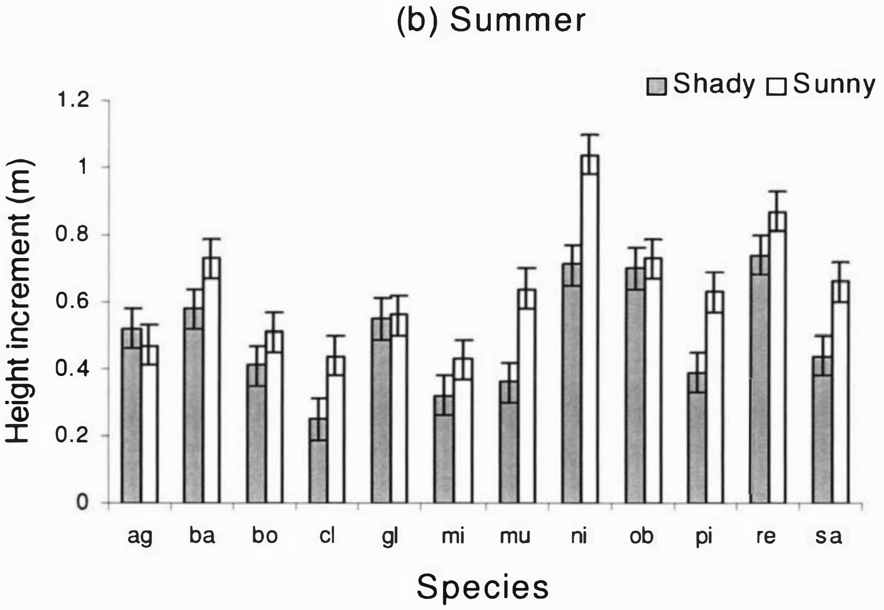
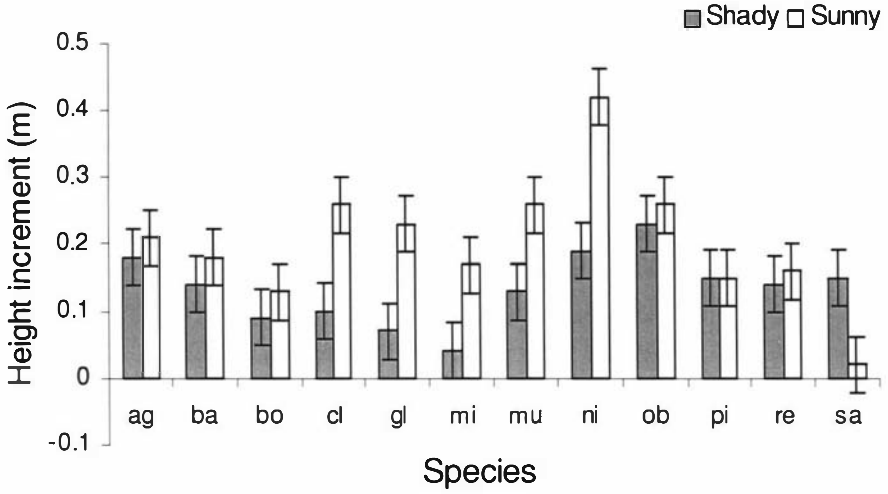
pi
re
sa
Species


(b) Summer
Shady
Sunny
Height increment (m)
1.2
1
0.8
0.6
0.4
0.2
0
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species

(c) Autumn



(d) Winter

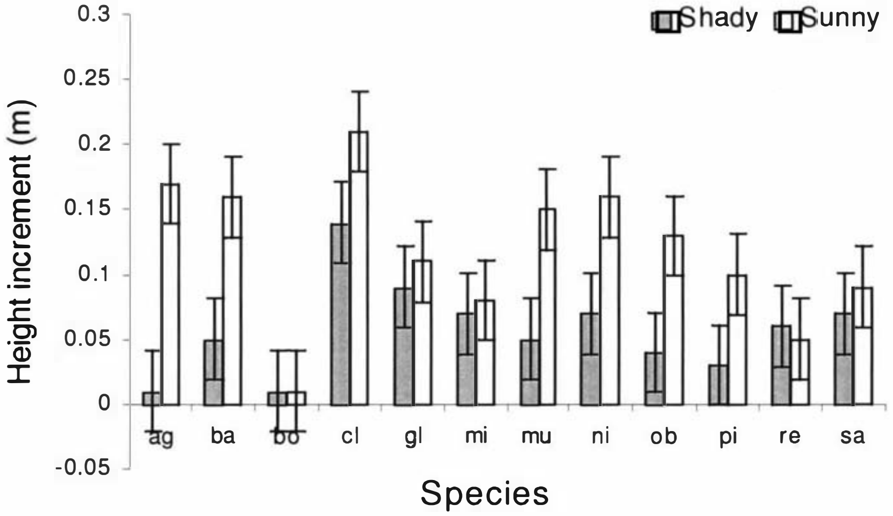


Figure 7.3 The interaction between species, season and aspect on mean seasonal height increment (m) for (a) spring, (b) summer, (c) autumn and (d) winter. Error bars = 2 x SEM.

There was a significant (P = 0.0001) interaction between species, year and season on height growth. Height growth in 1997/98 was similar to 1999/98 for most species in all seasons. During the spring the exceptions were *E. regnans* (better in 1997/98) and *E. saligna* (better in 1998/99) (Appendix 9a). Over the summer *E. muelleriana*, *E. nitens*, *E. obliqua* and *E. pilularis* were better in 1997/98 while *E. saligna* was better in 1998/99 (Appendix 9b). The autumn of 1997/98 was better than the autumn of 1998/99 in three species, *E. muelleriana*, *E. pilularis* and *E. saligna* (Appendix 9c). Winter height growth differences were also apparent in three species, E. *agglomerata* being better in 1997/98 while *E. obliqua* and *E. regnans*, both ash species, were better in 1998/99. Two notable but contrasting performances from different species are apparent in Appendix 9d. Winter height growth in *E. botryoides* was very low (not significantly different from zero) in both years, probably the result of possum damage (Section 7.4.8.2). *E. cladocalyx* on the other hand had significantly better height growth than all other species in 1998/99 and all other species in 1997/98 apart from *E. agglomerata* and *E. baxteri*. The growth of *E. cladocalyx* was mediocre in the spring and summer but better than average during the autumn. This resulted in autumn and winter growth contributing about 40% of annual height growth in *E. cladocalyx*, more than any for other species (Figure 7.5). Summer growth was correspondingly less important in this species. The contribution of autumn/winter growth to annual height growth was least in *E. botryoides* and in *E. saligna* (1998/99). Summer was the most important season for height growth in most species in both years.

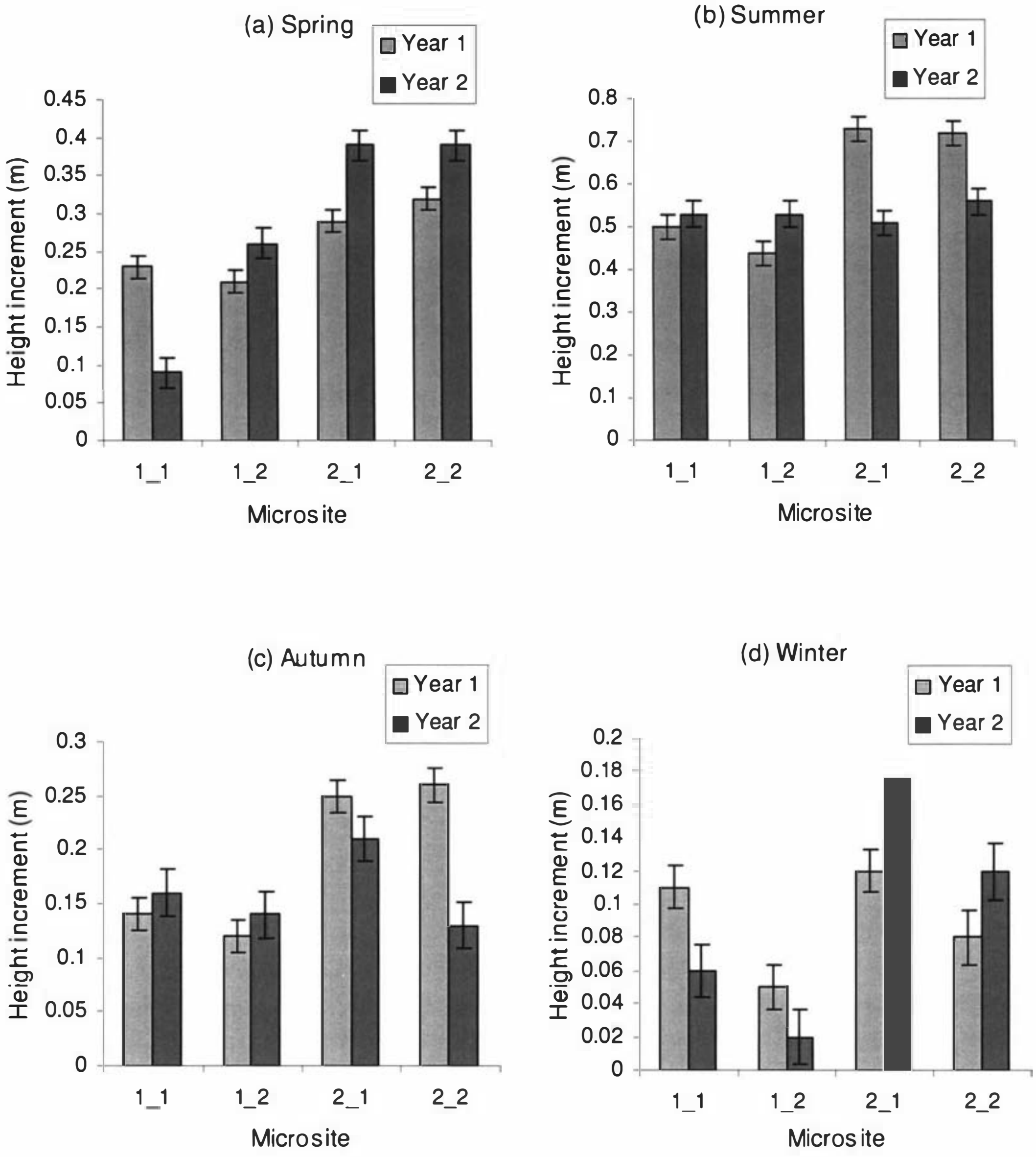
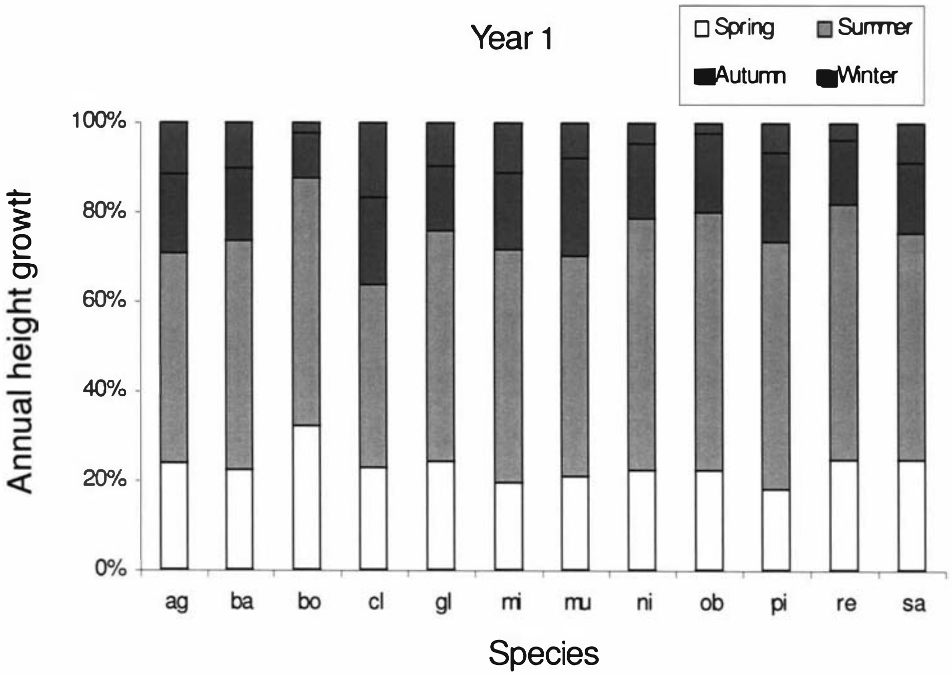


Figure 7.4 The interaction between season, year, slope aspect and slope position on height growth (m) during (a) spring, (b) summer, (c) autumn and (d) winter. Microsites: The first number represents aspect, 1 = shady and 2 = sunny, and the second represents slope position, 1 = upper and 2 = lower. Error bars = 2 x SEM.



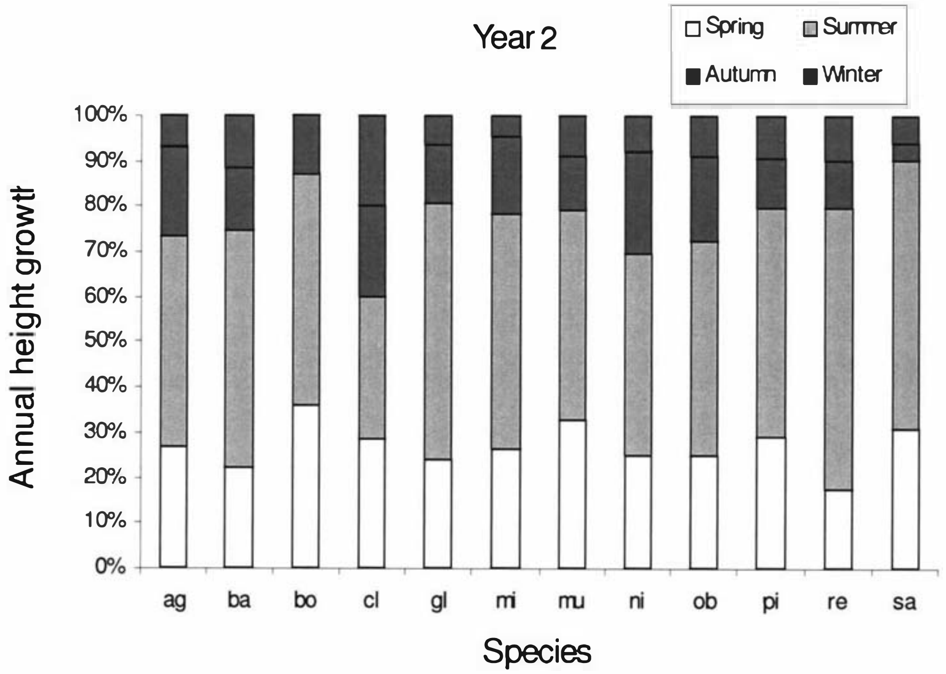


Figure 7.5 Proportional seasonal contribution (%) to annual height growth for each species in year 1 (September 1997 to August 1998) and year 2 (September 1998 to August 1999).

7.3 Annual growth

Height was measured annually between August 1997 and August 2000 and DBH annually between August 1998 and August 2000. Repeated measures ANOVA was used to determine if there were any interactions between treatments and time on growth. Plot means were used in all analyses.

7.3.1 DBH

There was a significant ($P < 0.0001$) age effect on DBH and there were significant interactions between age and species ($P < 0.0001$), age and aspect ($P = 0.004$) and age and slope position ($P = 0.02$). There were no three way or four way interactions. The differences between aspects and slope positions have increased over time (Table 7.3). At age 3 years the mean DBH of trees on the sunny aspect was 1 cm greater than on the shady aspect but by age 5 years the difference had doubled to 2 cm. Similarly the difference in mean DBH between the upper and lower slope increased from 0.4 cm to 0.9 cm at age 3 and 5 respectively, DBH being greater on the upper slope.

Species differences in DBH increased significantly between 3 and 5 years of age (Table 7.4 and Figure 7.6). *E. nitens* generally had greater DBH than all other species at all ages, the exceptions being *E. obliqua* and *E. regnans* at age 5. *E. microcorys* had significantly lower DBH than all other species at all ages. DBH increase over the two year period was least in *E. microcorys* (2.3 cm) and greatest in *E. obliqua* (6.7 cm). Species with intermediate DBH growth over this time included *E. botryoides*, *E. cladocalyx*, *E. saligna* and *E. pilularis* (3.2, 3.4, 4.3 and 4.5 cm respectively).

Table 7.3 The interactions between age (years) and slope aspect, and age and slope position, on mean DBH (cm).

		Age		
		3	4	5
Aspect				
	Shady	3.3	5.0	7.5
	Sunny	4.3	6.6	9.7
Position				
	Upper	4.0	6.0	9.2
	Lower	3.6	5.5	8.1
	SEM	0.12	0.20	0.27

Table 7.4 The interaction between age (years) and species on mean DBH (cm). Numbers in parentheses = SEM.

	Age		
	3	4	5
E. agglomerata	3.5 (0.27)	5.2 (0.44)	8.3 (0.59)
E. baxteri	4.0 (0.30)	6.4 (0.50)	10.0 (0.67)
E. botryoides	3.6 (0.27)	5.0 (0.44)	6.8 (0.60)
E. cladocalyx	3.3 (0.27)	4.6 (0.44)	6.7 (0.60)
E. globoidea	3.6 (0.30)	6.1 (0.50)	9.6 (0.67)
E. microcorys	2.1 (0.39)	2.8 (0.66)	4.4 (0.89)
E. muelleriana	3.9 (0.30)	5.9 (0.50)	9.1 (0.67)
E. nitens	6.0 (0.27)	8.6 (0.44)	12.0 (0.60)
E. obliqua	3.9 (0.27)	7.0 (0.44)	10.6 (0.60)
E. pilularis	3.5 (0.28)	5.3 (0.44)	8.0 (0.63)
E. regnans	4.4 (0.27)	6.6 (0.44)	10.5 (0.60)
E. saligna	3.8 (0.27)	5.7 (0.44)	8.1 (0.60)

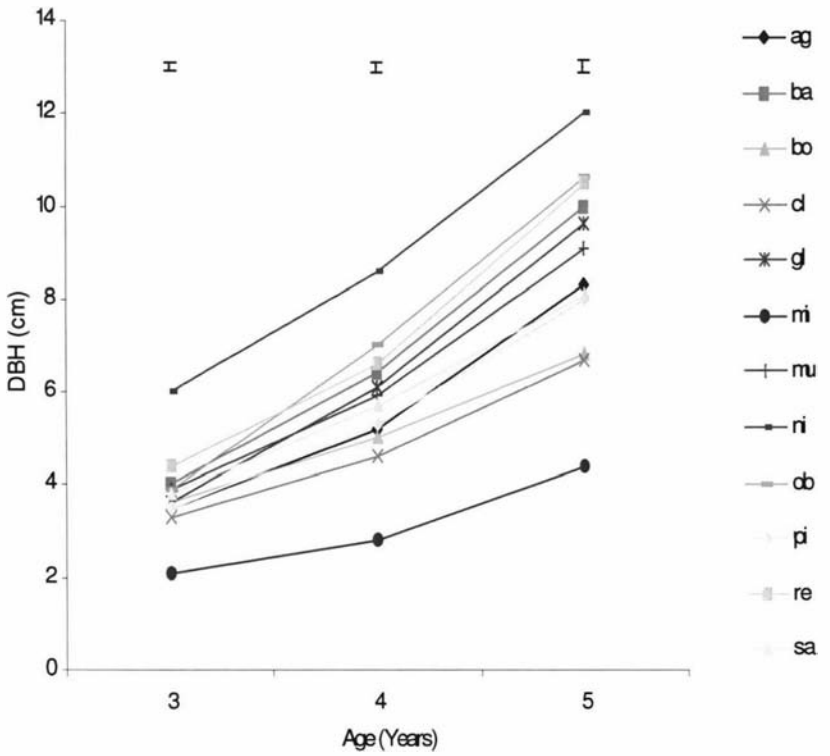


Figure 7.6 The interaction between age (years) and species on DBH (cm). Error bars = 2 x SEM.

7.3.2 Height

The pattern of height growth was similar to that of DBH. Mean height increased significantly over time ($P < 0.0001$) and there were significant interactions between age and species ($P < 0.0001$) and aspect ($P < 0.001$), however there was no interaction between age and slope position. At age 2 years there was little difference in height due to aspect, 1.7 m and 1.8 m for the sunny and shady faces respectively, but subsequently there was a divergence in mean aspect height so that by age 5 years height on the sunny face was 6.2 m while that on the shady face was 4.8 m (Table 7.5). Mean height on the sunny face was significantly ($P < 0.001$) higher than on the shady from age 3. Mean height was not influenced by slope position at any age.

Table 7.5 The influence of age (years), aspect, slope position and the interaction between age and aspect on mean height (m).

		Age			
		2	3	4	5
Aspect					
	Shady	1.7	2.6	3.5	4.8
	Sunny	1.8	3.2	4.4	6.2
Position					
	Upper	1.8	2.9	4.0	5.5
	Lower	1.8	2.9	3.9	5.5
	SEM	0.04	0.06	0.09	0.10

The interaction between species and age is shown in Figure 7.7. Species differences in mean height have increased with age. For example the difference between *E. nitens*, the best species at all ages, apart from *E. regnans* at age 2 years ($P < 0.02$), and *E. microcorys*, the poorest species at all ages ($P < 0.01$), has increased from 1.1 m (2 years) to 3.8 m (5 years). Between these species two distinct groups become apparent by age 5: A group of eight species comprising mostly stringybarks with intermediate height growth and the ashes, *E. obliqua* and *E. regnans*, achieving mean heights midway between *E. nitens* and the stringybarks.

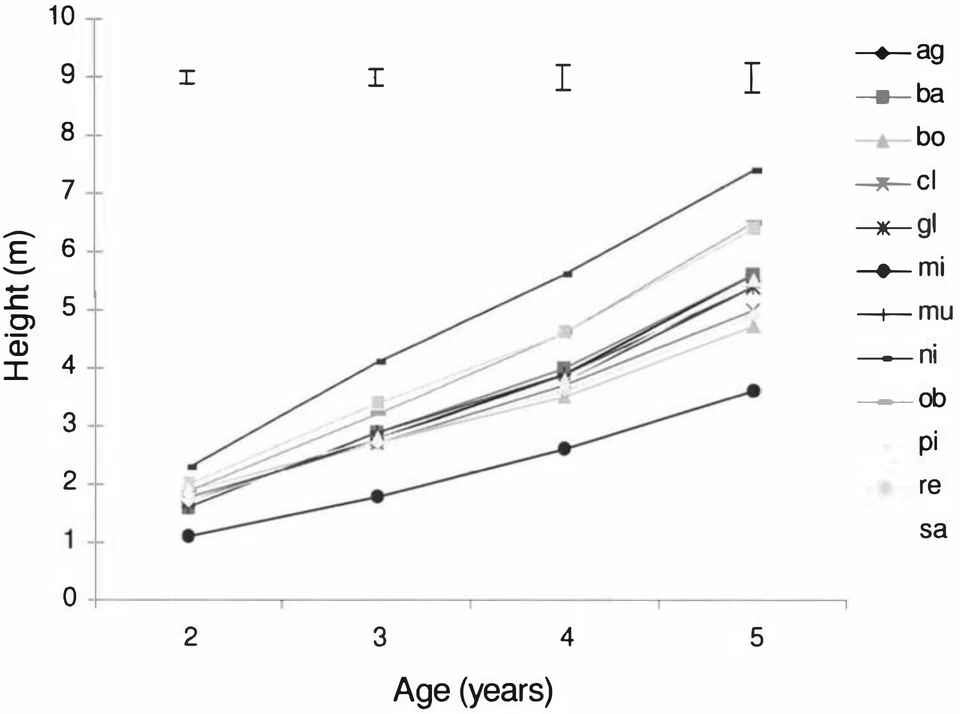


Figure 7.7 Interaction between age (years) and species on mean height (m). Error bars = 2 x SEM.

7.3.3 DBH:height ratio

DBH:height ratio's increased significantly with age ($P < 0.0001$) and there was a significant interaction between age and species ($P < 0.0001$). There was also a significant interaction between age and slope position ($P < 0.0005$).

The DBH:height ratio was greater on the upper slope position at all ages ($P < 0.05$) but the differences increased with age (Table 7.6) indicating that DBH growth is occurring at a faster rate relative to height growth on the upper slope. While

DBH:height ratio was significantly higher on the sunny face at age 3 years only, the interaction between age and aspect was not significant.

Table 7.6 The effects of age (years), aspect, slope position and the interaction between age and slope position on mean DBH:height ratio.

		Age		
		3	4	5
Aspect				
	Shady	1.07	1.29	1.49
	Sunny	1.14	1.34	1.51
Position				
	Upper	1.14	1.36	1.59
	Lower	1.06	1.26	1.41
	SEM	0.02	0.026	0.027

The interaction between age and species on DBH:height ratio is shown in Figure 7.8. *E. microcorys* had the lowest ratio at all ages though was not significantly lower than *E. cladocalyx* at age 5 years. *E. nitens* had the highest ratio at age 3 but by age 5 was intermediate. Species which experienced the largest increase included some of the stringybark species, for example *E. agglomerata* and *E. baxteri.* In contrast, *E. botryoides* and *E. saligna*, which at age 3 years had similar ratios, had significantly lower ratios than these species by age 5 ($P < 0.05$).

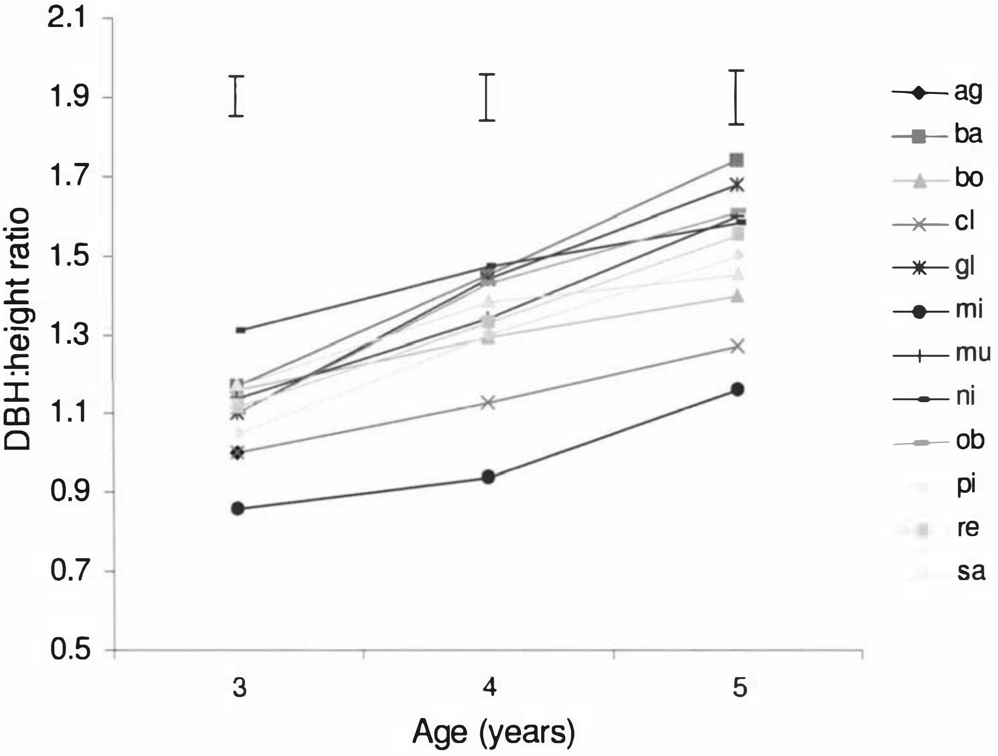


Figure 7.8 Interaction between species and age (years) on DBH:height ratio. Error bars = 2 x SEM.

7.4 Height, DBH, stem volume, stem form, wood density, plant health at age 5 years and root structure at age 6 years.

This section will present the results of the assessment carried out at age 5 years. Analysis of covariance, with the possum browse incidence recorded during establishment of the trial as the covariate, was used to determine the significance of microsite and species effects on DBH, height and stem volume. Analysis of covariance reduces error, increasing the precision of the analysis, and provides for the estimation of least squares means adjusted for the covariate (Steel & Torrie 1980). The relationship between diameter and height for individual species and microsites will be described and compared. Information on basic wood density collected from two sites in the Wairarapa will also be presented here. Whenever appropriate, details of methodology will be presented at the beginning of each subsection.

7.4.1 DBH

The effect of possum browse damage during establishment on DBH at age 5 years was significant ($P = 0.01$) and its inclusion as a covariate in the analysis resulted in an increased R^2 (increased from 0.76 and 0.78) and a reduction in the coefficient of variation (reduced from 23.7% to 22.9%).

The main effects of species ($P = 0.0002$), aspect ($P < 0.0001$) and slope position ($P = 0.001$) all significantly influenced DBH but no significant interactions occurred. *E. nitens* achieved the largest DBH at age 5 (12.2 cm), followed by a group of three species including *E. obliqua*, *E. regnans* and *E. baxteri* (10.2, 10.1 and 10.1 cm respectively) (Table 7.7). The poorest species, *E. microcorys*, had significantly smaller DBH (5.4 cm) than all other species apart from *E. cladocalyx* (6.2 cm) and *E. botryoides* (7.0 cm), less than half the DBH of the best species. There were significant differences in mean DBH among the stringybark species. The best of these was *E. baxteri,* which performed as well as the ash species, while *E. pilularis* was the poorest of this group (7.7 cm) significantly lower than *E. baxteri.* The sunny face (10.2 cm) produced trees with larger DBH than the shady face (7.1 cm). The effect of slope position was less marked, but the upper slope (9.3 cm) produced larger DBH than the lower slope (7.9 cm). Comparison of adjusted and unadjusted means reveals that mean DBH was similar to the mean adjusted for possum browse damage in most species. Exceptions were *E. microcorys*, *E. cladocalyx*, *E saligna*, *E. obliqua* and *E. regnans*. Species suffering more possum damage (Chapter 4) were adjusted up, most notably *E. microcorys* (0.9 cm) while those suffering less damage were adjusted down, principally *E. cladocalyx* (0.5 cm) and *E. obliqua* (0.4 cm). Mean DBH was adjusted up on the sunny face and down on the shady face, again, reflecting the relative incidence of possum damage during establishment. Slope position was not greatly affected.

Table 7.7 The effects of species, aspect and slope position on mean DBH (cm). Means adjusted for possum browse damage are compared with unadjusted means. Numbers in parentheses = SEM.

		Adjusted DBH	Unadjusted DBH
Species			
	E. agglomerata	8.3 (0.56)	8.3
	E. baxteri	10.1 (0.60)	10.0
	E. botryoides	7.0 (0.57)	6.8
	E. cladocalyx	6.2 (0.59)	6.7
	E. globoidea	8.7 (0.58)	9.0
	E. microcorys	5.4 (0.67)	4.5
	E. muelleriana	8.9 (0.61)	9.1
	E. nitens	12.2 (0.57)	12.0
	E. obliqua	10.2 (0.59)	10.6
	E. pilularis	7.7 (0.57)	7.8
	E. regnans	10.1 (0.59)	10.5
	E. saligna	8.5 (0.58)	8.1
Aspect			
	Shady	7.1 (0.29)	7.5
	Sunny	10.2 (0.29)	9.7
Position			
	Upper	9.3 (0.24)	9.2
	Lower	7.9 (0.25)	8.1

7.4.2 Height

The influence of possum browse damage on height growth was also significant (P = 0.02), increasing the R^2 from 0.81 to 0.82 and reducing the coefficient of variation from 17.1% to 14.6%. The effect of possum browsing during establishment was less than that for DBH which has resulted in a small number of means being adjusted. Species with mean height adjusted upwards include *E. microcorys* (0.4 m) (Table 7.8) while mean height was adjusted down in *E. cladocalyx* (0.2 m) and *E. obliqua*

(0.2 m), the same species to have DBH adjusted (Section 7.4.2).

Species performance for height was similar to that of DBH, *E. nitens* (7.5 m) being significantly better than all other species, followed by *E. regnans* (6.2 m) and *E. obliqua* (6.3 m). Similarly, *E. microcorys* (4.0 m) was significantly lower than all other species. The performance of the stringybark species was intermediate. *E. pilularis* was the poorest species in this group but differences were not significant. Mean height on the sunny face (6.3 m) was significantly greater than the shady (5.7 m). Slope position did not influence height.

Table 7.8 The effects of species, aspect and slope position on mean height (m). Means adjusted for possum browse damage are compared with unadjusted means. Numbers in parentheses = SEM.

		Adjusted Height	Unadjusted Height
Species			
	E. agglomerata	5.6 (0.23)	5.6
	E. baxteri	5.6 (0.25)	5.6
	E. botryoides	4.8 (0.23)	4.7
	E. cladocalyx	4.8 (0.24)	5.0
	E. globoidea	5.2 (0.24)	5.4
	E. microcorys	4.0 (0.27)	3.6
	E. muelleriana	5.3 (0.25)	5.4
	E. nitens	7.5 (0.23)	7.4
	E. obliqua	6.3 (0.24)	6.5
	E. pilularis	4.9 (0.23)	4.9
	E. regnans	6.2 (0.24)	6.4
	E. saligna	5.6 (0.24)	5.4
Aspect			
	Shady	4.7 (0.12)	4.8
	Sunny	6.3 (0.12)	6.2
Position			
	Upper	5.6 (0.10)	5.5
	Lower	5.4 (0.10)	5.5

7.4.3 DBH:height ratio

Possum browse damage significantly (P = 0.02) influenced the DBH:height ratio. The R^2 was increased slightly and coefficient of variation decreased slightly. Adjusted and unadjusted mean DBH:height ratios are shown in Table 7.9. *E. microcorys*, which was adjusted upwards from 1.16 to 1.25, a reflection of the upward adjustment in DBH in this species. There was little or no adjustment in other species.

There were significant species (P = 0.02) and slope position differences (P = 0.03) in DBH:height ratio. *E. baxteri* achieved the highest ratio (1.76), though not significantly higher than *E. muelleriana*, *E. nitens*, *E. globoidea* and *E. obliqua*. *E. cladocalyx* (1.23) and *E. microcorys* (1.25) achieved the lowest ratio's. The DBH:height ratio was significantly higher on the upper slope (1.61) than the lower slope (1.38).

Table 7.9 The effects of species, aspect and slope position on DBH:height ratio. Means adjusted for possum browse damage are compared with unadjusted means. Numbers in parentheses = SEM.

		Adjusted Ratio	Unadjusted Ratio
Species			
	E. agglomerata	1.46 (0.056)	1.47
	E. baxteri	1.76 (0.060)	1.75
	E. botryoides	1.41 (0.056)	1.40
	E. cladocalyx	1.23 (0.058)	1.27
	E. globoidea	1.58 (0.057)	1.61
	E. microcorys	1.25 (0.057)	1.16
	E. muelleriana	1.61 (0.060)	1.62
	E. nitens	1.60 (0.056)	1.59
	E. obliqua	1.58 (0.058)	1.62
	E. pilularis	1.48 (0.056)	1.49
	E. regnans	1.51 (0.058)	1.55
	E. saligna	1.48 (0.057)	1.45
Aspect			
	Shady	1.43 (0.029)	1.49
	Sunny	1.56 (0.029)	1.51
Position			
	Upper	1.61 (0.024)	1.60
	Lower	1.38 (0.024)	1.40

7.4.4 Stem volume

7.4.4.1 Methods

Individual stem volume was estimated by the use of an empirical function to calculate volume in the bottom section of the tree, which is below 1.4m, and a geometric function for the upper section. Smalian's formula (Ellis 1995) was used to estimate wood volume of the bottom section and the equation for the volume of a cone was used for the upper section: Total stem volume being the sum of the volumes in the upper and lower stem sections. Smalian's formula is routinely used in New Zealand to estimate the volume of logs. Information required include the diameter of the small end (in this case DBH) and the large end (0.1m) of the bottom section. The large end diameter was estimated by measuring the diameter of the stem at 0.1 m at age 5 years on two trees per plot: This allowed estimation of the average stem taper between 0.1 and 1.4 m in each plot. This in turn was used to estimate stem diameter at 0.1 m for all stems measured for DBH at age 5 years. Wood volumes (over bark) are expressed in cubic decimeters (dm^3). Smalian's formula and the formula for the volume of a cone are provided in Appendix 10.

7.4.4.2 Volume

Analysis of covariance revealed that possum damage significantly influenced individual stem volume at age 5 years ($P = 0.008$) with a corresponding small increase in R^2 and small decrease in the coefficient of variation. There were significant differences in stem volume between species ($P = 0.004$), aspect ($P = 0.006$) and slope position ($P= 0.05$). *E. nitens* (50.3 dm^3) produced greater mean individual stem volume at age 5 years than all other species. *E. regnans*, *E. obliqua* and *E. baxteri* constituted a second group. The remainder of the stringybarks were intermediate but produced less than 50% the stem volume of *E. nitens.* A group of the poorest species comprised *E. cladocalyx*, *E. microcorys* and *E. botryoides.* The effect of aspect was marked, trees on the sunny aspect (34.5 dm^3) producing more than twice the mean stem volume as those on the shady aspect (13.8 dm^3). The effect of slope position was less significant, trees on the lower slope producing (20.0 dm^3) while those on the upper slope produced (28.3 dm^3).

Table 7.10 The effects of species, aspect and slope position on individual stem volume (dm^3). Means adjusted for possum browse damage are compared with unadjusted means. Numbers in parentheses = SEM.

		Adjusted Volume	Unadjusted Volume
Species			
	E. agglomerata	19.8 (3.6)	20.1
	E. baxteri	29.4 (3.9)	28.6
	E. botryoides	14.5 (3.7)	13.3
	E. cladocalyx	11.0 (3.8)	13.8
	E. globoidea	22.8 (3.7)	25.1
	E. microcorys	12.5 (4.3)	6.1
	E. muelleriana	23.2 (3.9)	24.2
	E. nitens	50.3 (3.7)	48.9
	E. obliqua	31.0 (3.8)	33.8
	E. pilularis	18.0 (3.7)	18.9
	E. regnans	35.5 (3.8)	38.3
	E. saligna	22.1 (3.7)	19.7
Aspect			
	Shady	13.8 (1.9)	17.0
	Sunny	34.5 (1.9)	31.4
Position			
	Upper	28.3 (1.6)	27.1
	Lower	20.0 (1.6)	21.3

7.4.5 Relationship between DBH and height

7.4.5.1 Methods

The relationship between diameter and height for individual species and microsites will be described and compared, using Petterson functions. The relationship between DBH and height is useful for mensuration purposes because DBH is quick and simple to measure whereas tree heights can be very difficult and time consuming. If a relationship between DBH and height can be established, it is possible to estimate height from DBH. The Petterson function, a form of nonlinear regression, is normally used to describe the relationship between DBH and height in New Zealand. It is specific to individual species, sites and tree age (Goulding 1995). Detail of the Petterson function is provided in Appendix 11.

7.4.5.2 DBH-height curves

DBH-height curves for individual species are shown in Figure 7.9. The shapes of the curves vary for different species. The coefficients which determine the shape of these curves are detailed in Table 7.10. The β coefficient determines the asymptote of the curve (Woollons, 2003). Only the differences between the extreme values of both coefficients were significant. Note that in species such as *E. nitens* and *E. agglomerata*, which tend to have greater height at any given DBH, the coefficient β is low, whereas in *E. microcorys*, with trees of shorter stature at any given DBH, the β coefficient is high. The Petterson curves for individual microsites show similar variation (Figure 7.11). Trees on the sunny aspect are taller than those on the shady at any given DBH. β coefficients on the sunny aspect were significantly higher than those on the shady aspect but slope position had no effect. Microsite also influenced the α coefficient, the upper sunny microsite ($\alpha = 1.62$) being significantly higher than the shady microsites ($\alpha = 1.28$).

Scatterplots of DBH against height for each microsite (Figure 7.10) show some variation in tree height at any given DBH. This is reflected in the R^2 values shown in Table 7.11. These values were estimated by utilising a log reciprocal model rather than the Petterson equation above. This is because the R^2 values estimated with the Petterson equation are artificially high due to the DBH term appearing on both sides of the equation (Woollons 2003). The R^2 values for individual species ranged from 0.55 (*E. botryoides*) to 0.83 (*E. nitens*) and those for microsites between 0.69 and 0.80.

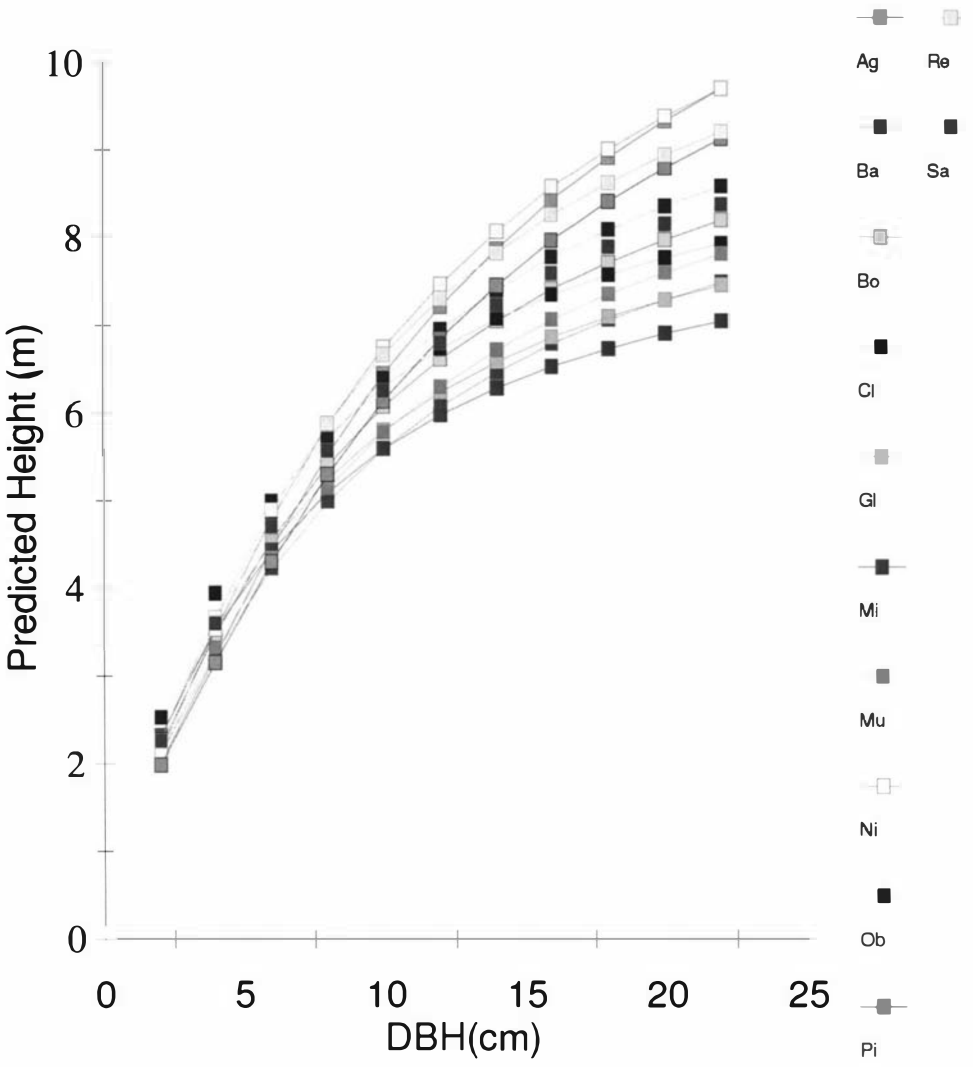
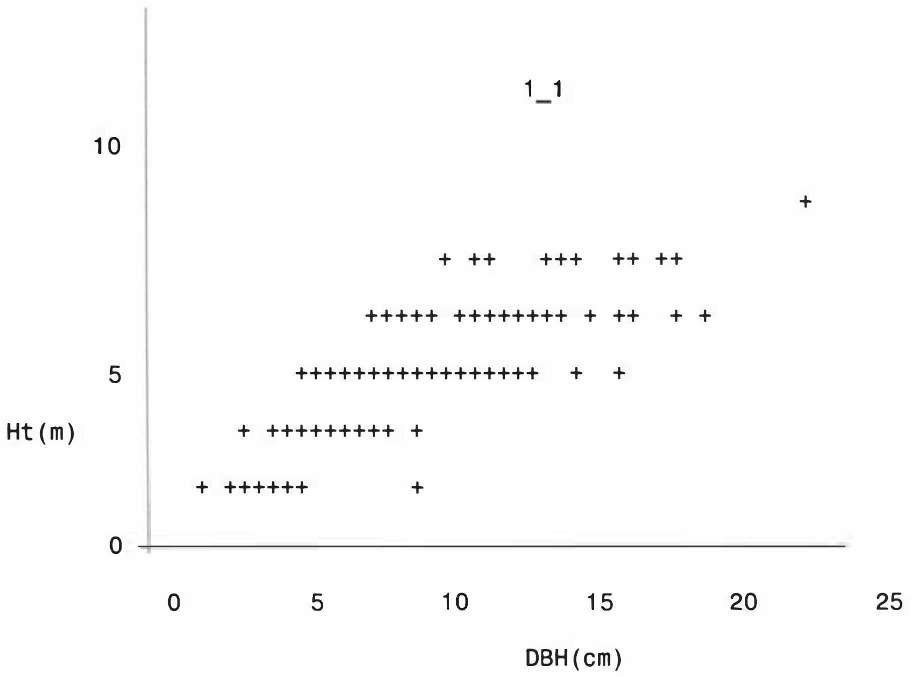
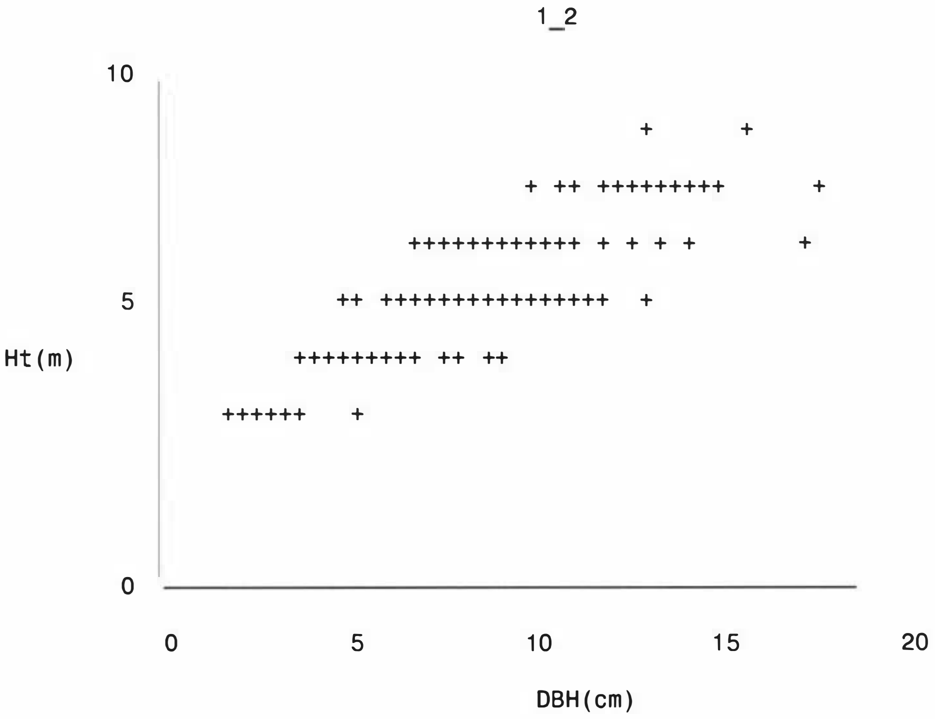
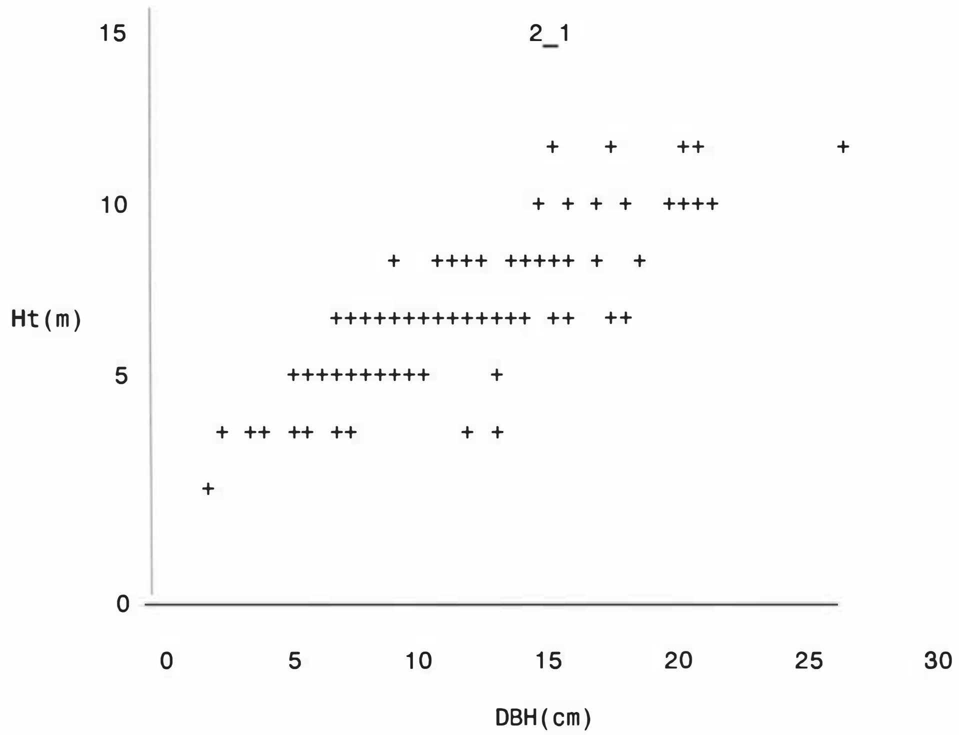


Figure 7.9 Petterson curves of the relationship between DBH (cm) and predicted height (m) for individual species.


1_1
10
5
0
Ht(m)
0
5
10
15
20
25
DBH(cm)


1_2
10
5
0
Ht(m)
0
5
10
15
20
DBH(cm)



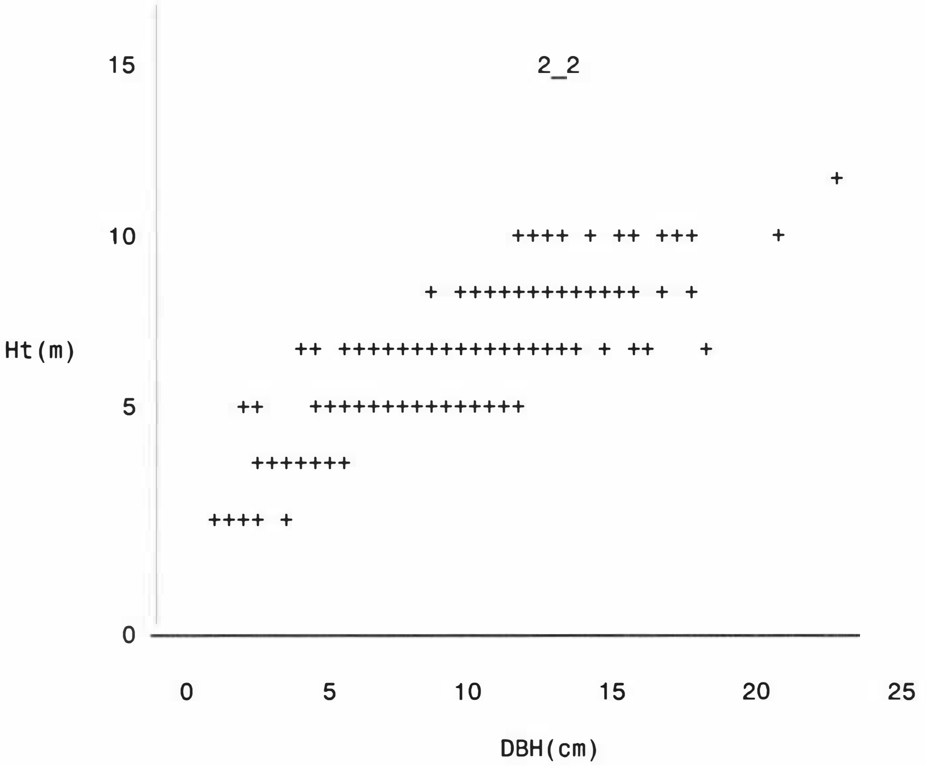


Figure 7.10 Scatterplot of DBH (cm) against height(m) at age 5 for individual microsites. Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope.

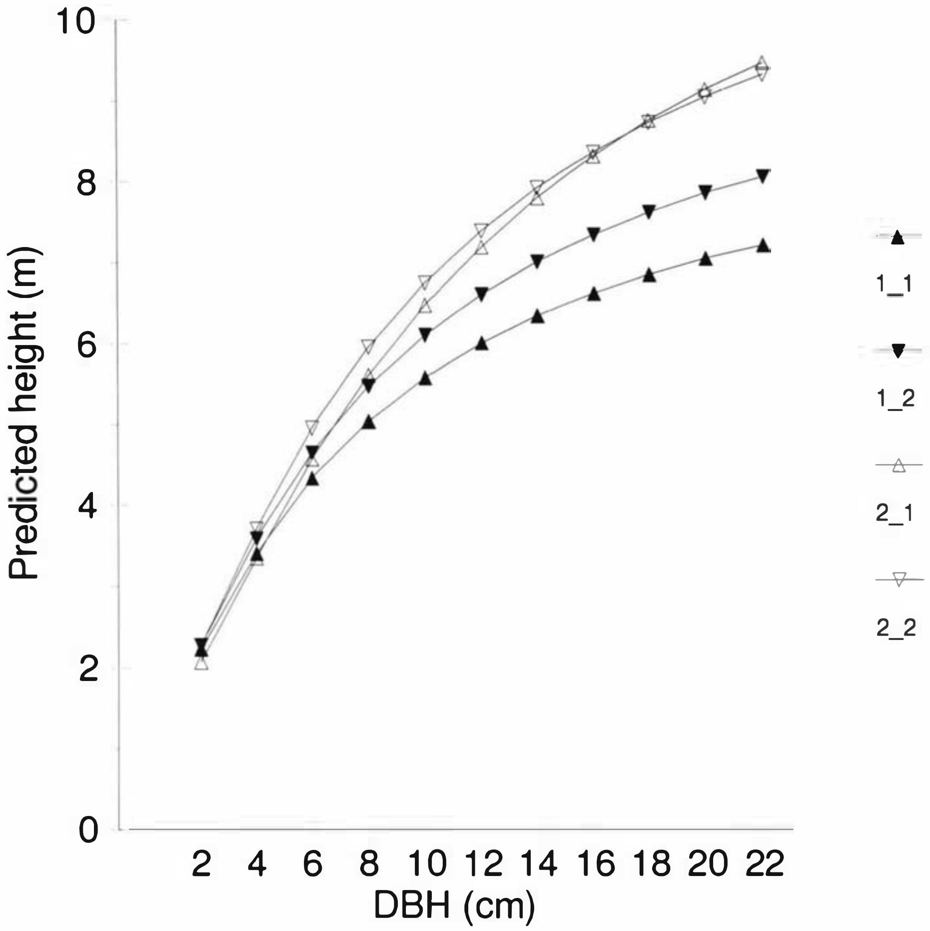


Figure 7.11 Petterson curves of the relationship between DBH (cm) and predicted height (m) for individual microsites. Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope.

Table 7.11 Regression coefficients of the Petterson DBH-height curves and coefficients of determination for species and microsites. Numbers in parentheses = coefficient SE. Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope. The coefficients for species and microsites were used to generate the relationships in Figures 7.9 and 7.11, respectively.

		α	β	R^2
Species				
	E. agglomerata	1.73 (0.135)	0.349 (0.0154)	0.66
	E. baxteri	1.42 (0.145)	0.417 (0.0141)	0.69
	E. botryoides	1.37 (0.128)	0.402 (0.0107)	0.55
	E. cladocalyx	1.05 (0.104)	0.424 (0.0135)	0.73
	E. globoidea	1.21 (0.113)	0.431 (0.0118)	0.75
	E. microcorys	1.16 (0.074)	0.447 (0.0155)	0.82
	E. muelleriana	1.43 (0.139)	0.410 (0.0145)	0.78
	E. nitens	1.51 (0.152)	0.356 (0.0118)	0.83
	E. obliqua	1.30 (0.156)	0.395 (0.0149)	0.68
	E. pilularis	1.74 (0.136)	0.362 (0.0157)	0.73
	E. regnans	1.37 (0.108)	0.377 (0.010)	0.78
	E. saligna	1.31 (0.116)	0.400 (0.0129)	0.64
Microsite				
	1_1	1.28 (0.066)	0.436 (0.0072)	0.69
	1_2	1.28 (0.053)	0.410 (0.0069)	0.80
	2_1	1.62 (0.082)	0.361 (0.0073)	0.76
	2_2	1.36 (0.069)	0.375 (0.0068)	0.69

7.4.6 Form

7.4.6.1 Methods

The form of the stem of each tree was assessed at age 5 years. Stem characteristics assessed included stem number, sweep, lean, kink, branch size, crown size and crown balance (Chapter 3). The score for individual trees was determined by summing the individual scores for the stem characteristics. Poor form is reflected by high scores. A check of the distribution of form revealed that the data were skewed to the right. To correct this the data were transformed by taking the natural logarithm (Steel & Torrie 1980) prior to ANOVA. In addition the number of trees in each plot categorised as acceptable (Chapter 3) was determined. The normal probability plot of this data appeared to follow the Poisson distribution, typical of count data: Consequently the square root transformation (Steel & Torrie 1980; Afifi & Clark 1996) was applied prior to analysis, which resulted in an approximately normal distribution. Transformed data are presented for both mean form score and number of acceptable trees per plot.

The influence of possum browsing during the establishment period was investigated as a possible covariant for both form score and count of acceptable trees. However, possum browsing at this time had no effect on either characteristic. Subsequent possum browsing, which was primarily confined to the eastern blue gums, *E. botryoides* and *E. saligna*, did negatively influence form in these species. The incidence of possum damage in the canopy of all trees was recorded during the winter from age 3 years.

7.4.6.2 Form score

There was considerable variation in the form score of trees throughout the trial. Common faults included both primary and secondary forking, particularly on the upper slope areas, as well as lean and sweep, which tended to be more prevalent in wetter areas such as near the toe of the slope or where seepage occurred. In *E. botryoides* and *E. saligna* possum browsing resulted in the tips of the main branches and the leader being broken (Plate 7.3). Many of these trees had poor form due to kinks in the main stem as well as large diameter branches.

There were significant species differences (P = 0.01) in mean form score (Table 7.12). *E. nitens* (1.2) had better form than any other species while *E. botryoides* (1.9) had poorer form than any other species. There were no differences in form among the stringybark species.

Table 7.12 Species means for assessed form score.

	Log Form
E. agglomerata	1.6
E. baxteri	1.7
E. botryoides	1.9
E. cladocalyx	1.6
E. globoidea	1.6
E. microcorys	1.6
E. muelleriana	1.7
E. nitens	1.2
E. obliqua	1.5
E. pilularis	1.6
E. regnans	1.7
E. saligna	1.7
SEM	0.05

None of the main microsite factors significantly influenced form but there was a significant interaction (P = 0.05) between aspect, slope position and species (Figure 7.12). *E. nitens* had better form than all other species apart from the upper shady microsite where it was similar to *E. obliqua* and *E. cladocalyx*. Form on the upper shady microsite was significantly poorer than for the other microsites. A similar pattern was observed in *E. agglomerata*, displaying significantly poorer form on the upper shady microsite than on the other microsites, where its form was generally intermediate. Two species displayed stable form across all four microsites, *E. microcorys* and *E. cladocalyx.* There was little difference in form between slope positions on the sunny face in all species.

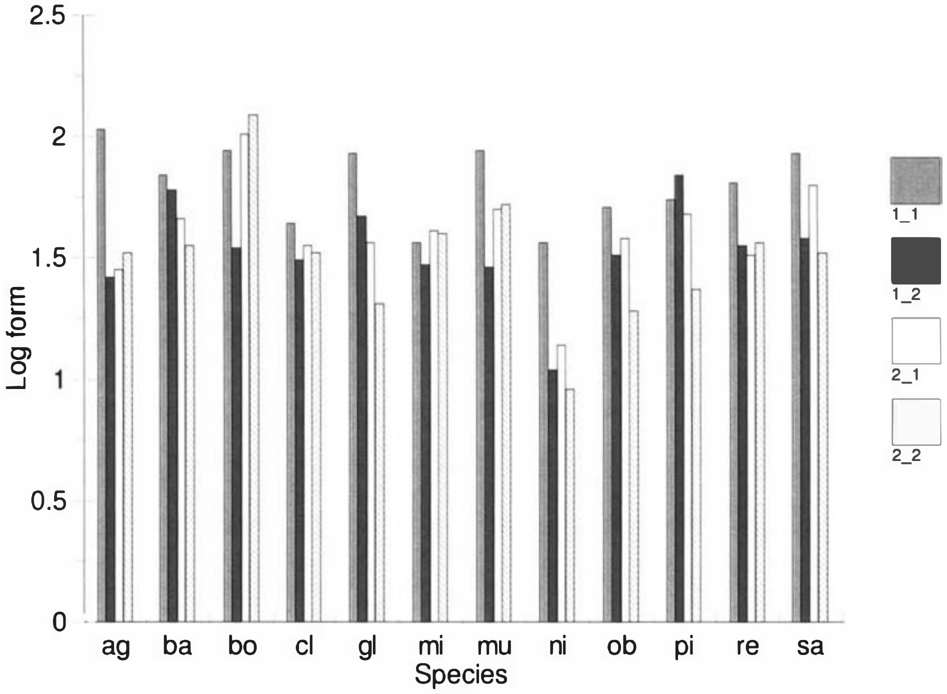


Figure 7.12 Interaction between species, aspect and slope position for mean form. Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope.

7.4.6.3 Acceptable trees

Microsite and species factors did not affect the number of acceptable trees per plot however there was a weakly significant (P = 0.055) species x aspect x slope position interaction on acceptable tree numbers (Figure 7.13). Acceptable tree numbers were not influenced by microsite in *E. baxteri*, *E. cladocalyx*, *E. microcorys*. *E. muelleriana*, *E. nitens* and *E. regnans* whereas in other species there was a strong microsite effect on acceptable tree numbers. For example, on the upper shady microsite there were no acceptable trees in *E. agglomerata* while remaining microsites produced similar numbers of acceptable trees in this species. In contrast *E. botryoides* produced significantly more acceptable trees on the lower shady microsite than the upper shady and lower sunny microsites, however the difference between slope positions on the sunny face was not significant. There was no difference between slope positions on the sunny aspect. The performance of *E. botryoides* on the sunny face was generally poor compared to most other species. *E. obliqua* produced more acceptable trees on the bottom slope positions than upper, though on the shady face the difference was marginally significant.

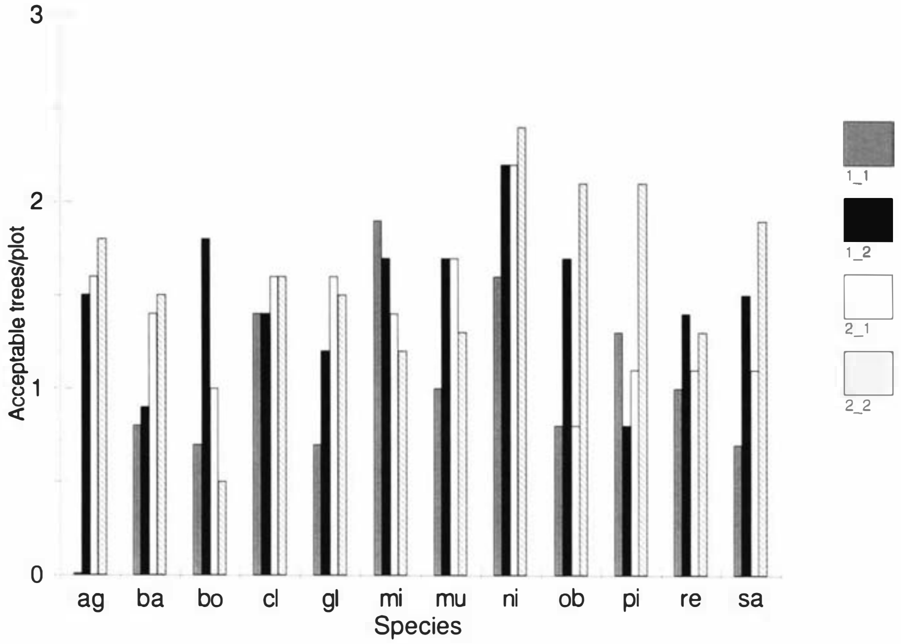


Figure 7.13 The interaction between species, aspect and slope position on the number of acceptable trees per plot (square root). Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope.

7.4.7 Basic wood density

7.4.7.1 Methods

Basic wood density (green volume/dry weight) at Tuapaka was measured at age 5 years by taking 5 mm diameter cores from two trees per plot. Trees with significant sweep or lean were excluded from sampling to ensure wood density measurements were not influenced by the presence of reaction wood. Cores were oriented radially to the centre of each tree (radius estimated from diameter measurement) and divided into inner and outer segments of approximately equal length. Basic wood density of each segment was measured separately. Wood density reported here includes inner, outer and the mean density. The relationship between wood density and diameter was also explored. In addition two *Eucalyptus* species evaluation trials in the Wairarapa were sampled for basic wood density (Chapter 3). Basic density was measured by taking a 5 mm diameter core oriented radially to the centre of each tree or, when the DBH of trees was greater than 40 cm, by taking a 200 mm core. The objective was to assess the potential relationship between basic wood density in 5 year old trees at Tuapaka with density from more mature trees (24 years) of the same species growing on a different site.

7.4.7.2 Tuapaka

There was a strong species effect on inner ($P = 0.001$), outer ($P < 0.0001$) and mean ($P < 0.0001$) basic wood density (Table 7.13). Mean basic wood density ranged from 413 kg/m^3 (*E. regnans*) to 594 kg/m^3 (*E. cladocalyx*). The other species to achieve mean wood density of 500 kg/m^3 or more were *E. agglomerata* (500 kg/m^3) and *E. microcorys* (532 kg/m^3). In contrast to its growth performance *E. nitens* had low wood density (426 kg/m^3). Comparison of the inner and outer stem basic densities shows that for most species the differences were minor or non existent. Exceptions included *E. baxteri*, *E. cladocalyx* and *E. regnans*. Inner wood density was greater than outer in *E. baxteri* and *E. regnans* whereas in *E. cladocalyx* outer density was greater. There were no significant microsite effects on density however there was a weak significant interaction (P = 0.055) between aspect and slope position on outer stem density. Outer stem density on the lower shady microsite (454 kg/m^3) was significantly lower than the upper shady microsite (479 kg/m^3), whereas on the sunny face density on the lower slope (497 kg/m^3) was slightly higher (though not significantly so) than on the upper slope (484 kg/m^3).

There was a significant interaction (P = 0.01) between species and aspect on mean basic density (Table 7.14). In most species densities were higher on the sunny face; however, the only species for which the aspect effect was significant was *E. globoidea*. In both *E. cladocalyx* and *E. saligna* density was slightly lower on the sunny face.

Diameter growth can influence wood density in some species, for example in *Pinus radiata* rapid diameter growth generally results in lower basic density (Hillis 1990). To investigate any potential relationship between diameter growth and wood density at Tuapaka DBH at age 5 years was correlated with mean basic wood density for each species. In most species there were no correlations between DBH and basic density. However, moderately strong positive correlations between DBH and inner (r = 0.65), outer (r = 0.61) and mean (r = 0.65) densities were identified in *E. microcorys* (Table 7.15). There were also weak positive correlations with outer stem wood density in *E. baxteri* (r = 0.48) and *E. muelleriana* (r = 0.54) and with mean density in *E. muelleriana* (r = 0.50).

Table 7.13 Species and microsite effects on radial variation and mean basic wood density (kg/m^3).

		Inner Stem	Outer Stem	Mean
Species				
	E. agglomerata	499	502	500
	E. baxteri	462	432	447
	E. botryoides	452	484	468
	E. cladocalyx	593	595	594
	E. globoidea	483	472	477
	E. microcorys	540	526	532
	E. muelleriana	489	497	493
	E. nitens	437	414	426
	E. obliqua	438	438	438
	E. pilularis	497	500	498
	E. regnans	426	400	413
	E. saligna	470	483	477
	SEM	13.7	12.6	11.8
Aspect				
	Shady	477	466	472
	Sunny	487	490	489
	SEM	5.4	4.9	4.6
Position				
	Upper	482	482	482
	Lower	483	475	479
	SEM	5.4	5.0	4.7

Table 7.14 Interaction between species and aspect on mean basic density (kg/m^3).

	Aspect	
	Shady	Sunny
E. agglomerata	493	508
E. baxteri	442	452
E. botryoides	464	472
E. cladocalyx	614	574
E. globoidea	453	501
E. microcorys	513	553
E. muelleriana	479	507
E. nitens	409	442
E. obliqua	435	441
E. pilularis	477	519
E. regnans	396	430
E. saligna	488	466
SEM	15.7	15.7

Table 7.15 Pearson correlation coefficients between DBH (cm) and basic wood density (kg/m^3) of the inner stem, outer stem and the mean for each species.

	Inner	Outer	Mean
E. agglomerata	0.05	-0.14	0.18
E. baxteri	-0.28	0.48*	0.17
E. botryoides	-0.30	0.19	0.00
E. cladocalyx	0.22	0.35	0.31
E. globoidea	0.07	0.10	0.09
E. microcorys	0.65**	0.61**	0.65**
E. muelleriana	0.50*	0.37	0.54*
E. nitens	-0.17	-0.17	-0.16
E. obliqua	-0.27	0.07	-0.09
E. pilularis	0.06	0.33	0.19
E. regnans	-0.11	0.03	-0.05
E. saligna	-0.13	0.14	-0.02

* ($P < 0.02$)

** ($P < 0.005$)

7.4.6.3 Wairarapa

Mean basic wood density and number of trees sampled for each species at each site are detailed in Table 7.16. Wood densities at both sites were greater than those at Tuapaka for the same species, the differences ranging between 83 (*E. obliqua*) to 210 kg/m^3 (*E. globoidea*), both from the Kahuiti site. There were significant differences between species at both sites. For example, *E. nitens*, *E. obliqua* and *E. regnans* generally had significantly lower basic density ($P = 0.05$) than the other species represented. Differences due to site were the exception however, the only example being *E. botryoides* which had significantly higher density at Pakaraka than at Kahuiti ($P = 0.05$). There were no provenance differences in *E. nitens*, *E. obliqua* and *E. regnans*.

Table 7.16 Mean basic wood density (kg/m^3), DBH (cm) and number of trees sampled for each species at each Wairarapa site. Numbers in parentheses = SEM.

	Basic density	Tree numbers	DBH
Kahuiti			
E. agglomerata	615 (17.9)	7	23.6
E. botryoides	559 (16.7)	8	33.5
E. cladocalyx	681 (28.2)	3	23.4
E. globoidea	687 (24.4)	4	33.9
E. muelleriana	644 (24.4)	4	36.1
E. nitens	583 (13.8)	12	31.3
E. obliqua	522 (11.8)	16	34.4
E. regnans	519 (11.8)	16	33.6
Pakaraka			
E. botryoides	675 (27.5)	4	46.3
E. globoidea	667 (24.6)	5	41.6
E. nitens	570 (27.5)	4	48.5
E. obliqua	539 (31.8)	3	50.0
E. regnans	468 (31.8)	3	47.3

A correlation analysis between wood density and DBH in the Wairarapa was also conducted. Due to the small numbers of individual trees sampled at Pakaraka the data from this site was combined with that from Kahuiti to produce a Wairarapa mean for each species. Basic density was not correlated with DBH in any species.

The Wairarapa species mean densities were plotted against species means from Tuapaka, using combined data. The regression between Tuapaka and Wairarapa densities is also included (Figure 7.14). The coefficient of determination for the regression was 0.64, which indicates that the relationship is moderately strong.

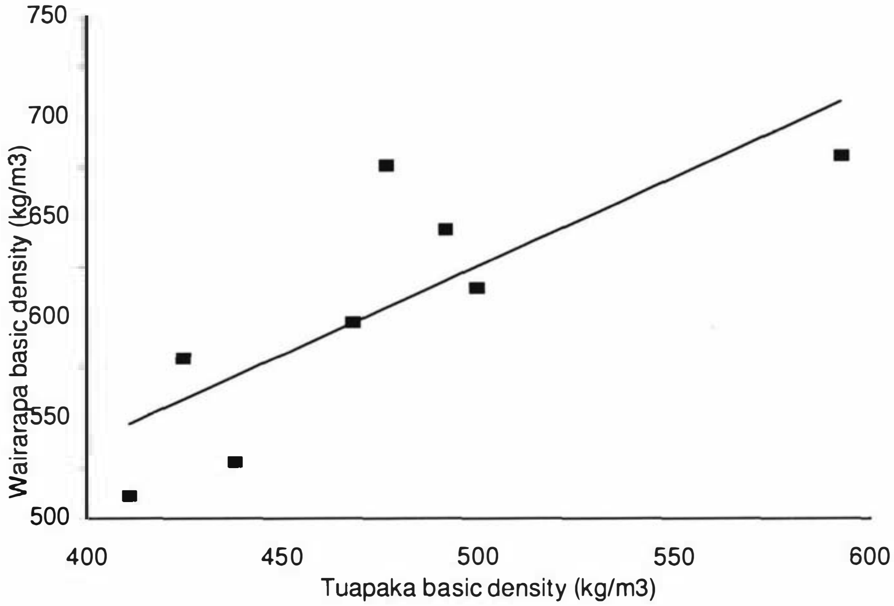


Figure 7.14 The relationship between mean basic wood density (kg/m^3) from Tuapaka and combined mean basic wood density from two Wairarapa sites. Regression equation: Wairarapa basic density = 183.7 + 0.884(Tuapaka basic density). $R^2 = 0.64$.

7.4.8 Pests and diseases

The trial site was monitored for pest and disease problems at each visit. During the establishment period (4 months) this was typically weekly but subsequently, monthly visits become the norm. The presence of a number of insect pests, mammals and fungal diseases were noted. These are briefly detailed below. *E. botryoides* and *E. saligna* suffered significant and persistent pest problems, notably possum browse damage during the winter months from age 3 years, and a eucalypt leaf gall caused by a wasp, *Ophelimus eucalypti*. The incidence of both pests was recorded during the winter assessment from age 3 years and in addition severity was recorded at age 5 years. Analysis of data of both pests is presented (Sections 7.4.8.1 and 7.4.8.2). A brief description of the other pests and diseases recorded at the trial site are listed below.

Fungal diseases

Mycosphaerella spp.

Foliar lesions consistent with *Mycosphaerella cryptica* (Ridley & Dick 2001) were noted on several species but most often on *E. nitens*, *E. obliqua* and *E. regnans*. Damage was mostly light and did not appear to influence the vigour of infected trees. An exception to this was a small amount of dieback in a few *E. nitens* trees, most noticeable in the late autumn, which may have resulted from *Mycosphaerella* cankers in small branches and twigs of these trees.

Fusarium oxysporum

Observations made on trees which had died about 1 year after planting, mostly from the ash group *(E. obliqua* and *E. regnans),* revealed that the dead trees suffered from blackening of the stem base and roots (Plate 7.1). *Fusarium oxysporum* was isolated from samples submitted to the Plant Health Group, Institute of Natural Resources, Massey University, (Hugh Neilson, Institute of Natural Resources, Massey University, personal communication). This organism causes stem and root rots in many plant species around the world including eucalypts (Garret 1970). Wet and windy weather resulted in a few trees toppling from about age 2 years, again mostly the ash species. The stem base and the roots of these trees displayed the same symptoms.

Insect pests

Gum emperor moth caterpillar (*Antheraea eucalypti*).

Defoliation by these large caterpillars (up to 10 cm in length) was noticeable during the autumn when they were nearing full size. All species suffered some damage but in the vast majority of cases it was very light. However a few trees suffered severe defoliation during the late summer of 1998 (2.5 years of age) on the upper shady microsite. Species involved were *E. botryoides* (two cases), *E. cladocalyx*, and *E. saligna*, (single cases). One *E. botryoides* tree died about a year after defoliation, during which no growth was made. This suggests that the death could be attributed to defoliation. Of the three surviving trees at age 5 years, two had mean height and DBH similar to the plot mean and the other (*E. saligna*) was well below the plot mean for both height and DBH. Consequently, it is difficult to make any firm conclusions concerning the long term effect of this defoliation.

Eucalyptus tortoise beetle (*Paropsis charybdis*)

The larvae of this beetle, and to a lesser extent the adults, are a potentially serious pest of some eucalypt species capable of completely defoliating trees (Bain 1977). Of the species present at Tuapaka *E. nitens* has been shown to be highly susceptible (Wilcox et al 1985). Larvae were only found once, on a *E. nitens* tree growing on the upper sunny face. Damage was very light and subsequent checks did not reveal significant defoliation.

7.4.8.1 *Eucalyptus* leaf gall (*Ophelimus eucalypti*)

Eucalyptus leaf gall is a recent arrival in New Zealand. In Australia it attacks a number of eucalypt species but in New Zealand serious damage has been limited to the eastern blue gums, *E. botryoides* and *E. saligna*. It was first detected in a single *E. saligna* tree in the autumn following planting but by the first winter (age 1 year) it was widespread in the eastern blue gum plots. The incidence of leaf gall increased over the following two years but by age 5 years the number of infected trees appeared to have stabilised (Table 7.17). Galls appear as small (up to 5-6 mm) raised spots, typically reddish in colour, on the surface of leaves (Plate 7.2).

After 5 years 68% of *E. botryoides* and 55% of *E. saligna* trees were infected. Rates of infection were consistently higher in *E. botryoides* but significantly higher only at ages 1 and 4. Initially rates of infection were greater on the shady aspect and upper slope position but from age 2 onward there were no microsite differences.

Table 7.17 The incidence (%) of trees infected with *Eucalyptus* leaf gall (*Ophelimus eucalypti*).

	Age (years)				
	1	2	3	4	5
Species					
E. botryoides	45	62	69	73	68
E. saligna	30	53	49	49	55
Aspect					
Shady	52	56	57	61	62
Sunny	23	59	61	61	60
Position					
Upper	48	63	60	60	62
Lower	27	52	58	62	60
SEM	3.5	7.4	7.5	5.4	4.6

Table 7.18 The effect on the severity of leaf gall score on DBH (cm) at age 5 years in *E. botryoides* and *E. saligna*. 0 = no gall, 1 = light infection, 2 = moderate to severe infection. Numbers in parentheses = SEM.

	Leaf Gall Score		
	0	1	2
E. botryoides	5.0 (0.21)	4.3 (0.28)	4.1 (0.29)
E. saligna	5.7 (0.2)	5.1 (0.4)	3.1 (1.1)

The incidence of leaf gall had no effect on height or DBH at age 5 years but DBH was significantly (P = 0.05) affected by the severity (assessed by visual score, Chapter 3) of leaf gall (Table 7.18). Light infection decreased DBH in both species (though not significantly) with a further small decrease when infection became moderate to severe in *E. botryoides* but a large decrease in *E. saligna*. Trees with a leaf gall score of 3 had significantly lower mean DBH (4.1 and 3.1 cm for *E. botryoides* and *E. saligna*, respectively) than those which scored 0 (5.0 and 5.7 cm for *E. botryoides* and *E. saligna*, respectively). Microsite also influenced the severity of leaf gall infection. A higher % of trees suffered moderate to severe leaf gall on the sunny aspect (47%) compared with the shady (19%) with a corresponding decrease in the % of lightly infected trees on the sunny aspect.

7.4.8.2 Possum browsing

Possum browsing was a problem immediately after planting and control measures were introduced at that time (Chapter 4). Immediately post control possum damage was insignificant but during the winter of 1998 (age 3 years) possum damage in *E. botryoides* and *E. saligna* became noticeable (Plate 7.3). No control measures were taken at this time or subsequently because the damage was primarily confined to these two species and did not appear to have the potential to kill large numbers of trees. Although repeated severe defoliation by possums can kill trees (Piracy & Kean 1969) damage did not extend to complete defoliation and was confined to the winter period.

Browsing was light during the winter of 1998 and 1999 in both species but increased significantly (P = 0.05) in 2000 in *E. botryoides*, the incidence of browsing ranging from 11.5% to 23.0% (Table 7.19), whereas in *E. saligna* 2000 browsing damage was similar to previous years, significantly lower than *E. botryoides* apart from the bottom shady microsite. Browsing was generally lighter on the shady aspect, particularly on the bottom slope (P = 0.05) but in *E. saligna* browsing in 2000 was similar on all microsites.

Table 7.19 Incidence (%) of possum browse damage in *E. botryoides* and *E. saligna* on different microsites during the winter periods 1998 1999 and 2000. Microsite: 1_1 = shady upper slope, 1_2 = shady lower slope, 2_1 = sunny upper slope, 2_2 = sunny lower slope.

	Microsite				
	1_1	1_2	2_1	2_2	
E. botryoides					SEM
1998	5.4	1.3	7.5	10.9	1.5
1999	9.5	2.0	9.5	10.9	1.5
2000	18.8	11.5	23.0	20.4	2.2
E. saligna					
1998	2.9	1.7	8.8	8.8	1.6
1999	7.1	0	8.6	6.1	1.6
2000	10.0	7.9	11.3	6.1	2.6

Plate 7.1 Young *E. obliqua* tree showing root and basal stem rot attributed to *Fusarium oxysporum*. The lignotuber is also visible at the base of the stem.

Plate 7.2 Eucalypt leaf galls caused by *Ophelimus eucalypti* on immature *E. botryoides* leaves at Tuapaka.

Plate 7.3 Possum damage in canopy of 4 year old *E. botryoides* tree at Tuapaka.

7.4.9 Branch shedding

7.4.9.1 Methods

Eucalypts are generally intolerant of competition and shade. One of the consequences of this intolerance is the characteristic of shedding or self pruning of bottom branches, particularly in the sapling stage (Florence 1996). This is a potentially useful characteristic for foresters because it reduces tending costs where the objective is to produce clearwood from the butt log (Barr 1996). The self pruning ability of the Tuapaka trees was assessed by measuring the height to the bottom live branch of all trees at age 5 years. To assess the relative height to the bottom live branch, the height of the bottom live branch was also expressed as a % of tree height. Plot means were subjected to ANOVA.

7.4.9.2 Bottom live branch height

ANOVA revealed strong species ($P = 0.0004$), aspect ($P = 0.005$) and slope position ($P = 0.01$) affects on mean height to the bottom live branch (Table 7.20). The height of the bottom live branch was greatest in *E. cladocalyx* (1.15 m) and *E. botryoides* (1.05 m), significantly higher than all other species. An intermediate group of species comprised *E. nitens*, and *E. saligna*, which had significantly higher bottom live branch height than remaining species apart from *E. globoidea*. The relative height of the bottom live branch was also greatest in *E. cladocalyx* (25.3%) and *E. botryoides* (24.3%). In contrast, the ash species, *E regnans* and *E. obliqua*, had relative bottom live branch heights of 6.4 and 6.7% respectively and, along with *E. muelleriana*, the only species with relative bottom branch height of < 10%.

Bottom live branch height was greater on the sunny aspect and the bottom slope however this was due to greater mean heights on these microsites. The relative heights of the bottom live branch of different aspects and slope positions were very similar (Table 7.20).

Table 7.20 The effects of species, aspect and slope on the height (m) and relative height (%) of the bottom live branch.

	Height of bottom live branch	Relative height of bottom live branch
Species		
E. agglomerata	0.63	11.5
E. baxteri	0.56	10.5
E. botryoides	1.05	24.3
E. cladocalyx	1.15	25.3
E. globoidea	0.72	13.7
E. microcorys	0.35	10.4
E. muelleriana	0.40	9.1
E. nitens	0.83	12.7
E. obliqua	0.43	6.7
E. pilularis	0.62	13.5
E. regnans	0.37	6.4
E. saligna	0.81	16.4
SEM	0.06	1.3
Aspect		
Shady	0.58	13.3
Sunny	0.74	13.4
SEM	0.03	NS
Slope position		
Upper	0.58	12.3
Lower	0.75	14.5
SEM	0.03	NS

7.4.10 Root structure

7.4.10.1 Methods

Six trees of two species (*E. nitens* and *E. saligna*) were excavated to allow assessment of the number and distribution of roots at age 6 years. Sampled trees, (one from each replicate) were randomly taken from the lower slope of both aspects. The number of major lateral roots (≥ 1.0 cm diameter) was counted and their cross sectional area at a point 10 cm from the bole measured. The radial distribution of laterals was scored using Menzies' scoring system (Chapter 3). The diameter at the base of the stem was also measured on all trees. All count data were subjected to the square root transformation but where treatment means were not found to be different means calculated from untransformed data are presented.

7.4.10.2 Lateral root number, distribution and cross sectional area

There was considerable variation in major lateral root number which ranged from three to 14 laterals per tree, however, there were no species or aspect effects on mean root number (Table 7.21). Similarly, there were no differences in mean individual lateral root cross sectional area (CA) or total lateral root CA per tree. There were no interactions between aspect and species for root number, individual root CA or total root CA.

The distribution of lateral roots was generally good. Of the 12 trees assessed 10 achieved a lateral root score of either zero (laterals in all quadrants) or 2 (laterals in three quadrants). The remaining two trees achieved lateral scores of 4 (laterals in two adjacent quadrants). Examples of root boles with different root distributions are shown in Plate 7.4. There were no species or aspect differences in lateral root score. The distribution of lateral roots with respect to slope and predominant winds (westerly and easterly through gully) was also assessed by counting the number of lateral roots in the uphill and downhill quadrants and those in the western and eastern quadrants, perpendicular to slope. The number of roots in each quadrant pairing was not influenced by species or aspect but there were significantly more roots (P = 0.002) in the quadrants aligned with slope compared to those perpendicular to the slope (Table 7.22). The difference in root numbers in each quadrant pairing was significantly affected by aspect (P = 0.007) but not by species, the difference being greatest on the shady face.

The relationships between total root number, total root CA, individual root CA and stem base CA was examined with the aid of correlation analysis (Table 7.23). There was a very strong correlation between stem base CA and total root CA (r = 0.97). A scatterplot of total root CA and stem base CA for all trees is shown in Figure 7.15. The slope of the linear regression of this data (not shown) is close to 1.0 (0.93 ± 0.08). Stem base CA was also moderately positively correlated with root number (r = 0.66) and strongly correlated with individual root CA (r = 0.92). Total root CA was strongly correlated with root number (r = 0.73).

Table 7.21 The effect of aspect and species on the mean number (roots/tree), mean individual cross sectional area (CA) (cm^2) and total CA (cm^2) of the major lateral roots (≥ 1.0 cm).

	Root number	Individual CA	Total CA
Species			
E. nitens	8.7	14.0	132.1
E. saligna	9.8	8.7	94.8
Significance	NS	NS	NS
Aspect			
Shady	9.5	11.0	112.9
Sunny	9.0	11.7	114.1
Significance	NS	NS	NS

Table 7.22 The effect of species and aspect on the number of lateral roots in quadrants aligned with slope and with predominant wind directions. The transformed (square root) mean differences between the numbers of lateral roots in each quadrant pairing are also presented.

	Slope	Wind	Difference
Species			
E. nitens	5.2	3.2	1.4
E. saligna	5.5	3.7	1.1
Significance	NS	NS	NS
Aspect			
Shady	5.8	3.0	1.65
Sunny	4.8	3.8	0.80
Significance	NS	NS	0.007

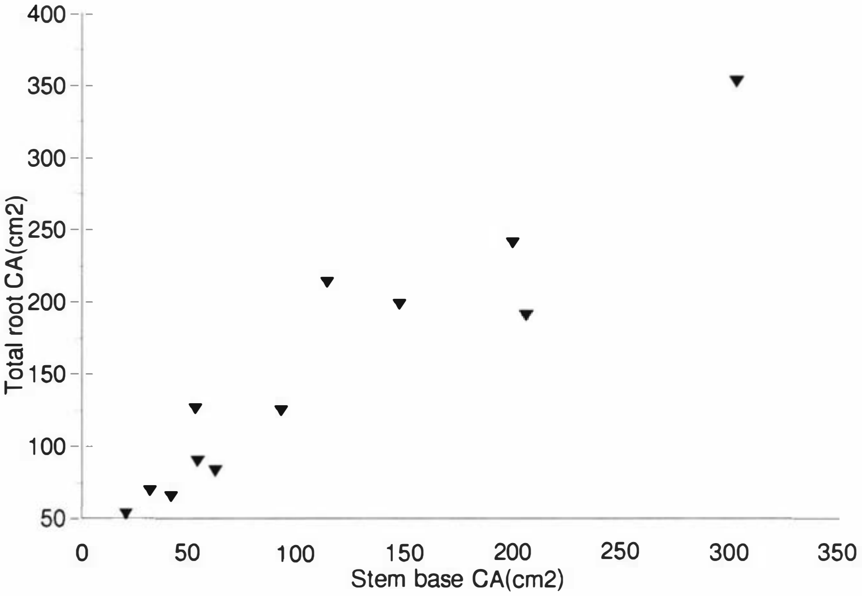


Figure 7.15 The scatterplot of stem base cross sectional area (CA) (cm^2) and total lateral root CA (cm^2).

Table 7.23 Pearson correlation coefficients between total lateral root number, mean individual root cross sectional area (CA) (cm^2), total root CA (cm^2) and stem base CA (cm^2). Correlations underlined are significant at $P < 0.02$ and those in bold at $P < 0.001$.

	Root number	Individual CA	Total CA
Ind. root CA	0.42		
Total root CA	0.72	**0.92**	
Stem base CA	0.66	**0.92**	**0.97**

Table 7.24 Intercepts, slopes and R^2 values of the regression between the natural logarithm of root CA and root number for each treatment and aspect (Figure 7.18). Numbers in parentheses = SEM.

	Slope	Intercept	R^2
Species x aspect			
E. nitens - sun	-0.146 (0.013)	1.9 (0.07)	0.96
E. nitens - shade	-0.114 (0.007)	1.5 (0.04)	0.98
E. saligna - sun	-0.184 (0.018)	1.5 (0.09)	0.96
E. saligna - shade	-0.116 (0.009)	1.6 (0.05)	0.97
Aspect			
Shady	-0.115 (0.008)	1.6 (0.04)	0.98
Sunny	-0.155 (0.013)	1.7 (0.07)	0.97

Plate 7.4 Examples of lateral root scores. Top: Laterals in all quadrants, score = 0. Bottom: Laterals in two adjacent quadrants, score = 4.

7.4.10.3 The relative contribution of individual roots to total root cross sectional area

The relative contribution of individual root CA to total CA provides an indication of possible differences in the allocation of resources to roots (Nicol et al 1995). To investigate this, the mean contribution of individual roots to total root CA for each treatment was initially plotted against the cumulative CA. This showed that about 90% of the total root CA is contributed by the seven largest roots in all treatments (Figure 7.16). Consequently only the largest roots were included in subsequent analyses. The plots in Figure 7.16 initially show a steep increase for all treatments before levelling off to reach about 90% of the total CA after inclusion of the 7th largest root. The two largest roots contribute from 46% (*E. saligna*, shady face) to 61% (*E. nitens*, shady face), of the total root CA. The mean CA of the seven largest roots in each treatment were plotted and compared (Figure 7.17). This revealed considerable differences between treatments. For example the CA of root 1 in *E. nitens* on the sunny face was about 50 cm^2 whereas the CA of root 1 in *E. saligna* on the sunny face was about 20 cm^2. However, the differences in CA's of lower order roots steadily declined, the seventh root having similar CA in all treatments.

The relationships between CA and root order in Figure 7.17 were non linear and displayed curve flattening at the end of the data range, typical of logarithmic relationships (Steel & Torrie 1980). Consequently the logarithmic (natural) transformation was utilised in an attempt to produce a linear relationship between CA and root number. The log transformed CA data for each treatment were plotted against root number (Figure 7.18) which resulted in linear curves. The linear regression lines for each treatment are included in Figure 7.18. Comparison of the intercepts from each regression indicated significant differences (Table 7.24). The intercept of the regression for *E. nitens* on the sunny slope was significantly higher than the other intercepts ($P < 0.05$) and the slope for *E. saligna* on the sunny face was greater than either species on the shady face ($P < 0.05$). To test the mean aspect effect the regressions between log transformed CA data for each aspect was calculated (Table 7.24). The intercepts were not different but the slope on the sunny face was significantly greater than on the shady ($P < 0.05$). This indicated that trees on the shady face allocated more assimilates to fewer large roots whereas on the sunny face assimilates were allocated more evenly.

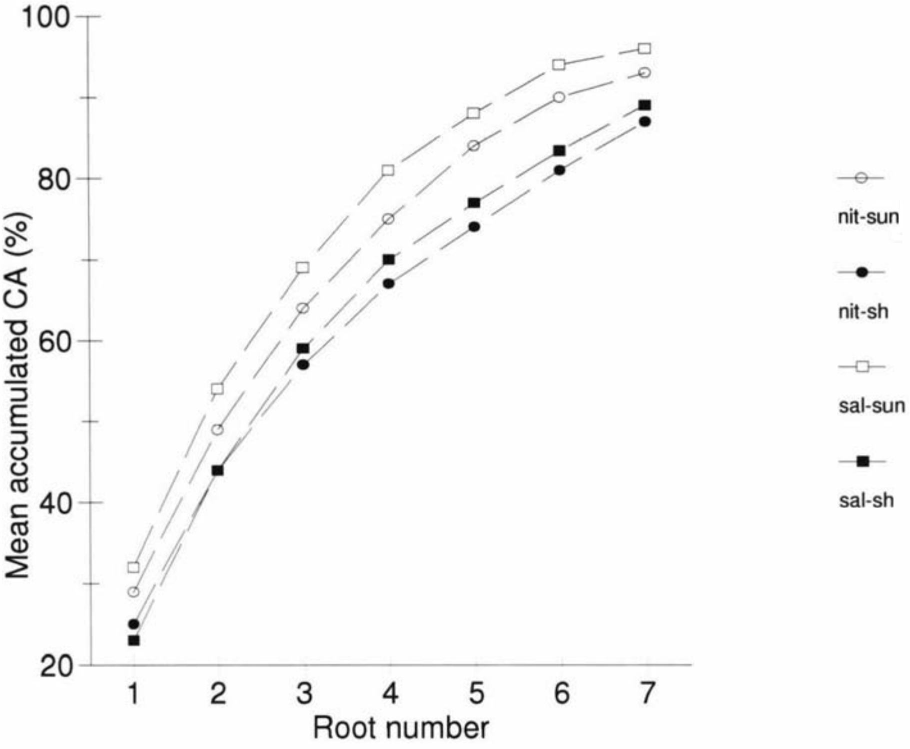


Figure 7.16 The mean contribution of the seven largest lateral roots (1 = largest) to total root cross sectional area (CA) (cm^2) for each species on each aspect.

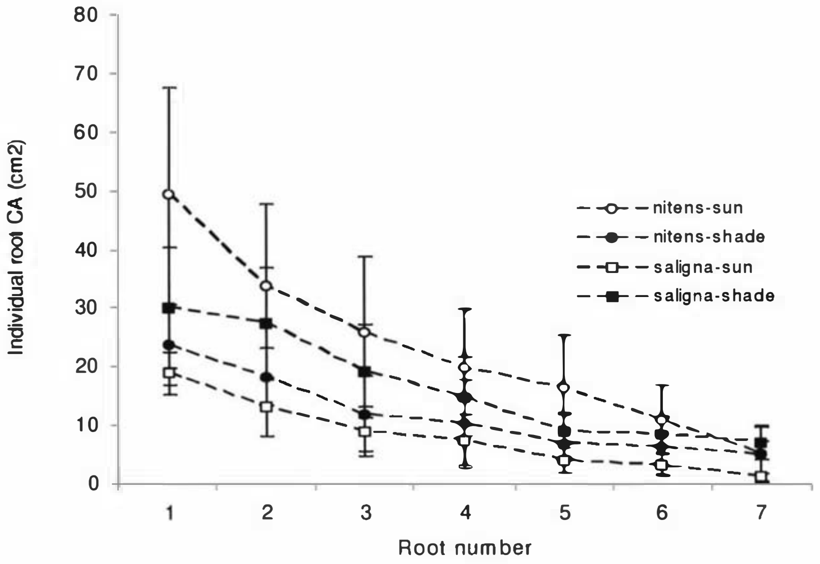


Figure 7.17 Mean individual root cross sectional area (CA) (cm^2) for the 7 largest roots for each species and aspect. Error bars = 2 x SEM.

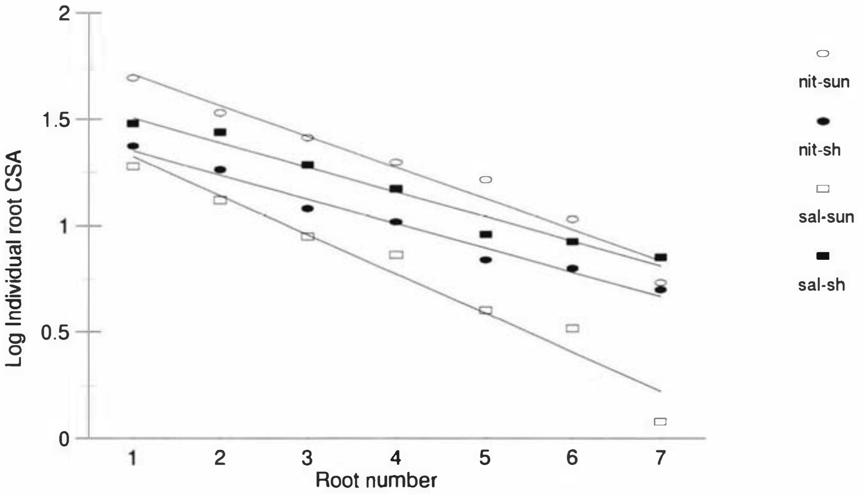


Figure 7.18 Natural logarithm of mean individual root cross sectional area (CA) for the seven largest roots for each species and aspect.

7.5 Survival to age 5 years

7.5.1 Methods

The proportion of surviving trees at age 5 years was determined by dividing the number of trees remaining in each plot by seven. Apart from dead trees remaining trees also excluded runts (trees too small to measure DBH), however, there were few trees (23 total) in this category. This measure of survival applies to the post establishment period only, all plots being blanked in the autumn following planting (Chapter 3). The distribution of % survival was skewed (left), consequently, the logarithmic (natural) transformation was applied prior to analysis (Steel & Torrie 1980).

7.5.2 Survival %

Percentage survival to age 5 years for individual species ranged from 72.6% (*E. microcorys*) to 98.0% (*E. nitens*), most species achieving > 80% survival. Mean survival (transformed) for species, aspect and slope positions are shown in Table 7.25. There were no differences in survival among species or for the main microsite factors. However, there was a significant interaction ($P = 0.04$) between aspect and slope position, survival on the upper sunny slope being lower than on the lower sunny slope, whereas on the shady face slope position had no effect.

Table 7.25 The effects of species, aspect and slope position on mean % survival (Log transformed) at age 5 years.

	Survival
Species	
E. agglomerata	4.4
E. baxteri	4.4
E. botryoides	4.5
E. cladocalyx	4.4
E. globoidea	4.5
E. microcorys	4.2
E. muelleriana	4.4
E. nitens	4.6
E. obliqua	4.2
E. pilularis	4.3
E. regnans	4.4
E. saligna	4.5
Significance	NS
Aspect	
Shady	4.5
Sunny	4.3
Significance	NS
Slope position	
Upper	4.4
Lower	4.4
Significance	NS
Aspect x Slope position	
Upper shady	4.5
Lower shady	4.4
Upper sunny	4.2
lower sunny	4.4
Significance	0.04

7.6 Relationships between foliage nutrients and DBH and height at age 5 years

Foliage nutrient concentrations at age 30 months (Chapter 6) and the N:P ratio were correlated with DBH, height and the DBH:height ratio at ages 3, 4 and 5 years. The resulting coefficients were similar across years, consequently only the age 5 coefficients are presented (Table 7.26). The N:P ratio was included because it has been reported to be associated with growth in eucalypts in some studies (Judd et al 1996a).

The majority of the significant correlations involved DBH and were mostly confined to *Symphyomyrtus* species including positive correlations between N and DBH (*E. microcorys*, *E. nitens*, and *E. saligna*), negative correlations between Mg and both DBH and height (*E. cladocalyx*, *E. globoidea*, *E. microcorys*, *E. nitens* and *E. regnans*) and for K, negative correlations with DBH in three species (*E. microcorys*, *E. nitens* and *E. saligna*) but a positive correlation with DBH in *E. muelleriana*. There were no significant correlations between nutrient concentrations and DBH or height in *E. baxteri*, *E. botryoides*, *E. globoidea* and *E. obliqua*. The DBH:height ratio was positively correlated with N and K in four species (*E. microcorys*, *E. muelleriana*, *E. nitens* and *E. saligna*) but was negatively correlated with Ca and/or Mg in five species (*E. baxteri*, *E. cladocalyx*, *E. microcorys*, *E. nitens*, and *E. regnans*). The N:P ratio was not correlated with height in any species but was moderately positively correlated with DBH in *E. regnans* and DBH:height in *E. microcorys* and *E. regnans*. The nutrient least associated with growth was P, being correlated with height in one species only (*E. agglomerata*).

When the data were divided into two strata, representing subgenera, the correlations between foliar nutrients and growth were generally weak and only the correlation between N and DBH was significant in *Monocalyptus* (Table 7.27).

Table 7.26 Pearson correlation matrices between foliar macronutrient concentrations (mg/g DM) and the N:P ratio with DBH (cm), height (m) and the DBH:height ratio at age 5 years for each species. Correlations underlined are significant at P ≤0.05 and those in bold at P ≤0.01.

	N	P	K	Ca	Mg	N:P	N	P	K	Ca	Mg	N:P
E. agglomerata							E. baxteri					
DBH	-0.10	0.39	-0.07	0.16	-0.21	-0.28	0.44	0.23	0.36	-0.45	-0.40	0.10
Height	-0.22	0.59	-0.04	0.21	-0.09	-0.49	0.27	0.25	0.30	-0.29	-0.40	-0.07
DBH:Height	0.31	-0.52	-0.15	-0.12	-0.34	0.57	0.51	0.18	0.34	-0.58	-0.34	0.24
E. botryoides							E. cladocalyx					
DBH	0.41	0.19	0.43	-0.36	-0.17	0.16	0.26	-0.07	0.35	-0.46	**-0.74**	0.48
Height	0.16	0.06	0.41	-0.30	-0.35	0.08	0.07	-0.12	0.26	-0.29	**-0.80**	0.28
DBH:Height	0.46	0.22	0.18	-0.22	-0.20	0.18	0.55	0.15	0.51	-0.63	-0.50	0.65
E. globoidea							E. microcorys					
DBH	0.47	-0.01	0.10	-0.06	-0.57	0.32	0.58	0.40	0.67	-0.66	**-0.71**	0.29
Height	0.56	0.18	0.08	-0.07	-0.46	0.13	0.49	0.33	0.60	-0.57	**-0.70**	0.26
DBH:Height	0.52	0.04	0.06	-0.07	-0.49	0.35	**0.76**	0.50	**0.72**	**-0.80**	**-0.74**	0.42
E. muelleriana							E. nitens					
DBH	0.52	0.22	**0.71**	-0.13	-0.17	0.10	**0.72**	0.50	0.62	-0.41	-0.60	0.55
Height	0.38	0.46	0.57	-0.09	-0.14	-0.14	0.47	0.41	0.30	-0.19	-0.33	0.28
DBH:Height	0.59	-0.23	0.62	-0.20	-0.20	0.48	0.66	0.44	**0.73**	-0.46	-0.59	0.52
E. obliqua							E. pilularis					
DBH	0.29	0.10	0.05	-0.18	-0.16	0.01	0.21	0.10	0.51	-0.32	-0.13	0.10
Height	-0.04	0.22	0.01	-0.02	-0.11	-0.20	0.20	0.24	0.40	-0.21	-0.04	-0.04
DBH:Height	0.45	-0.02	0.12	-0.26	0.09	0.17	0.08	-0.34	0.51	-0.46	-0.34	0.38
E. regnans							E. saligna					
DBH	0.51	-0.35	0.44	-0.49	-0.61	0.64	0.58	0.49	0.64	-0.55	-0.54	0.40
Height	0.42	-0.25	0.35	-0.46	-0.46	0.50	0.36	0.30	0.49	-0.42	-0.44	0.25
DBH:Height	0.51	-0.37	0.50	-0.45	**-0.70**	0.65	**0.70**	0.55	0.63	-0.55	-0.46	0.50

Table 7.27 Pearson correlation matrices between foliar macro-nutrient concentrations (mg/g DM), height (m) and DBH (cm) at age 5 years for each subgenus. Correlations underlined are significant at P ≤0.05 and those in bold at P ≤0.0001.

	N	P	K	Ca	Mg
Symphyomyrtus					
DBH	**0.42**	0.19	0.32	-0.23	-0.28
Height	0.34	0.32	0.23	-0.09	-0.18
Monocalyptus					
DBH	0.30	0.13	0.23	-0.24	-0.23
Height	0.19	0.07	0.13	-0.14	-0.21

The significant correlations between DBH and height and foliar nutrient concentrations were examined in more detail with the use of Scatterplots (Figures 7.19 to 7.27). Most plots suggest that, over the range of nutrient concentrations measured at Tuapaka, the relationships between nutrient concentrations and growth are linear. Possible exceptions include the relationships between foliar Mg and DBH (Figure 7.20) and height (Figure 7.21) in *E. cladocalyx*, which suggest a non linear relationship. A logarithmic function was fitted in both cases, resulting in a small increase in the R^2 (from 0.54 to 0.56) for the relationship between Mg and DBH and a moderate increase (0.63 to 0.67) for the relationship between Mg and height in *E. cladocalyx.* The plot of DBH and Mg in *E. regnans* (Figure 7.26) also suggested a non linear relationship, and a logarithmic fit also resulted in a moderate increase in the R^2 (0.38 to 0.43).

Possible aspect effects were assessed by the use of different symbols to represent each aspect in the scatterplots (▲ = sunny face, ■ = shady face). This reveals that points at each end of the data range tended to represent different aspects but there is some overlap in most plots while in some plots, for example N and DBH in *E. nitens* (Figure 7.25) and *E. saligna* (Figure 7.27) and between K and DBH in *E. muelleriana* (Figure 7.24), there is considerable overlap. However, the relationship between N and DBH in *E. saligna* did appear to be influenced by aspect (Figure 7.27). Points representing the shady face suggest a negative correlation. Separate analyses confirmed this. The correlation between N and DBH on the sunny face was 0.98 and highly significant (P = 0.0006), despite only 4 degrees of freedom, however there was no correlation between N and DBH on the shady face.

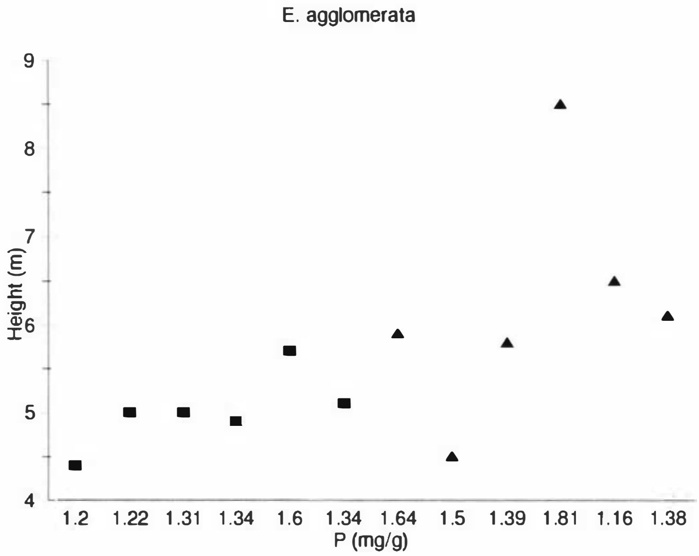


Figure 7.19 Scatterplot of the relationship between foliar P concentration (mg/g DM) and mean height (m) in *E. agglomerata* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

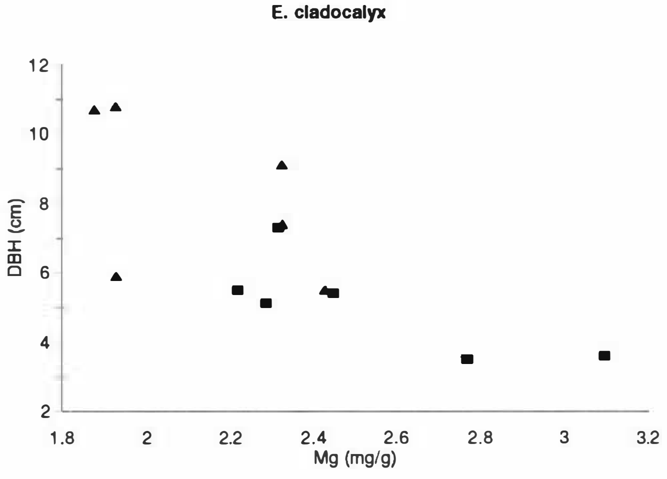


Figure 7.20 Scatterplot of the relationship between foliar Mg concentration (mg/g DM) and mean DBH (cm) in *E. cladocalyx* at age 5 years. Symbols: ▲ = sunny face, ■= shady face.

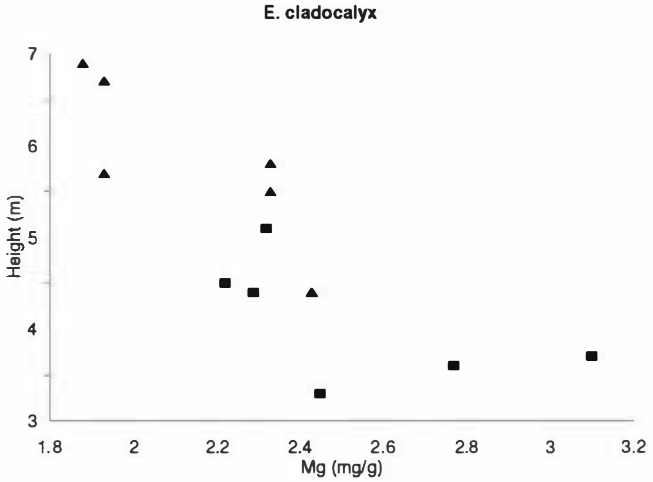


Figure 7.21 Scatterplot of the relationship between foliar Mg concentration (mg/g DM) and mean height (m) in *E. cladocalyx* at age 5 years. Symbols: ▲ = sunny face, ■= shady face.

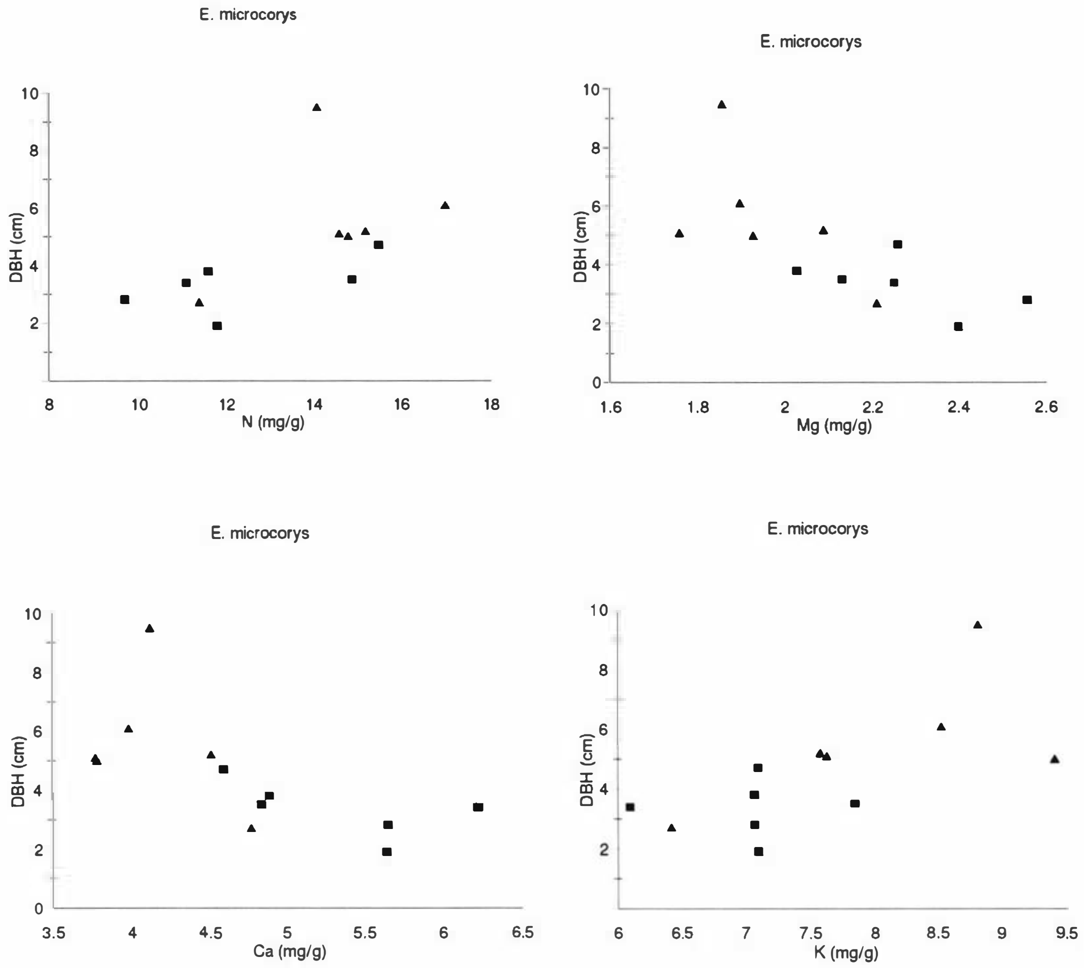


Figure 7.22 Scatterplots of the relationship between mean DBH (cm) and foliar nutrient concentrations (mg/g DM) of N (top left), Mg (top right), Ca (bottom left) and K (bottom right) in *E. microcorys* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

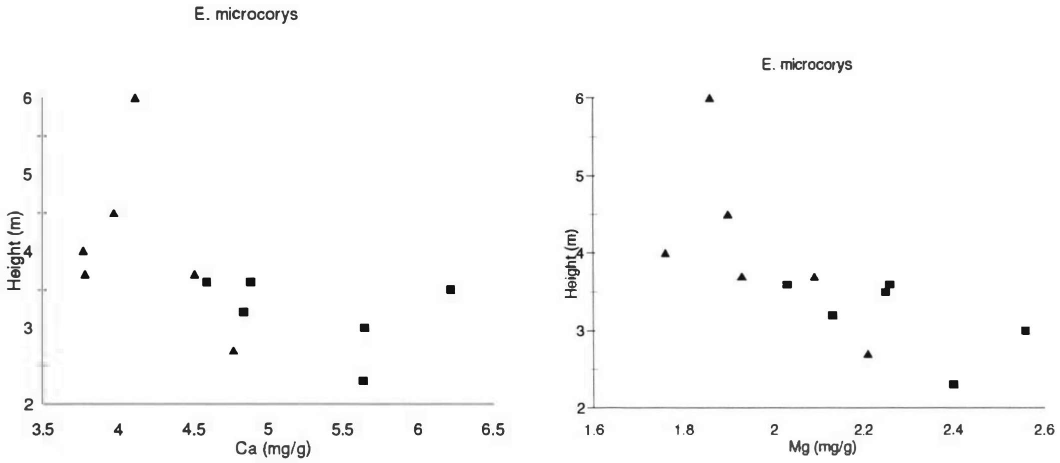


Figure 7.23 Scatterplots of the relationship between mean height (m) and foliar nutrient concentrations (mg/g DM) of Ca (left) and Mg (right) in *E. microcorys* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

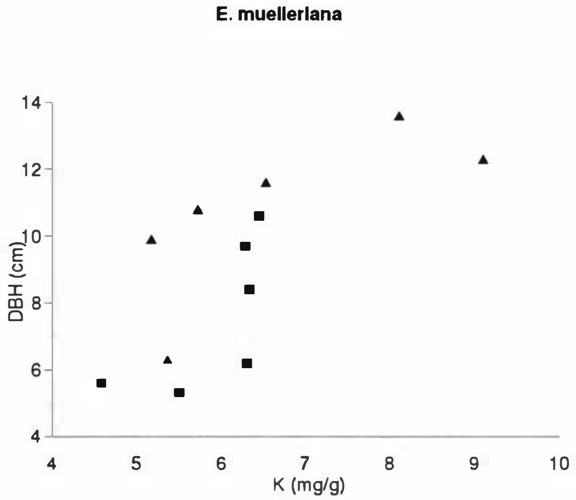


Figure 7.24 Scatterplot of the relationship between mean DBH (cm) and foliar K concentration (mg/g DM) in *E. muelleriana* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

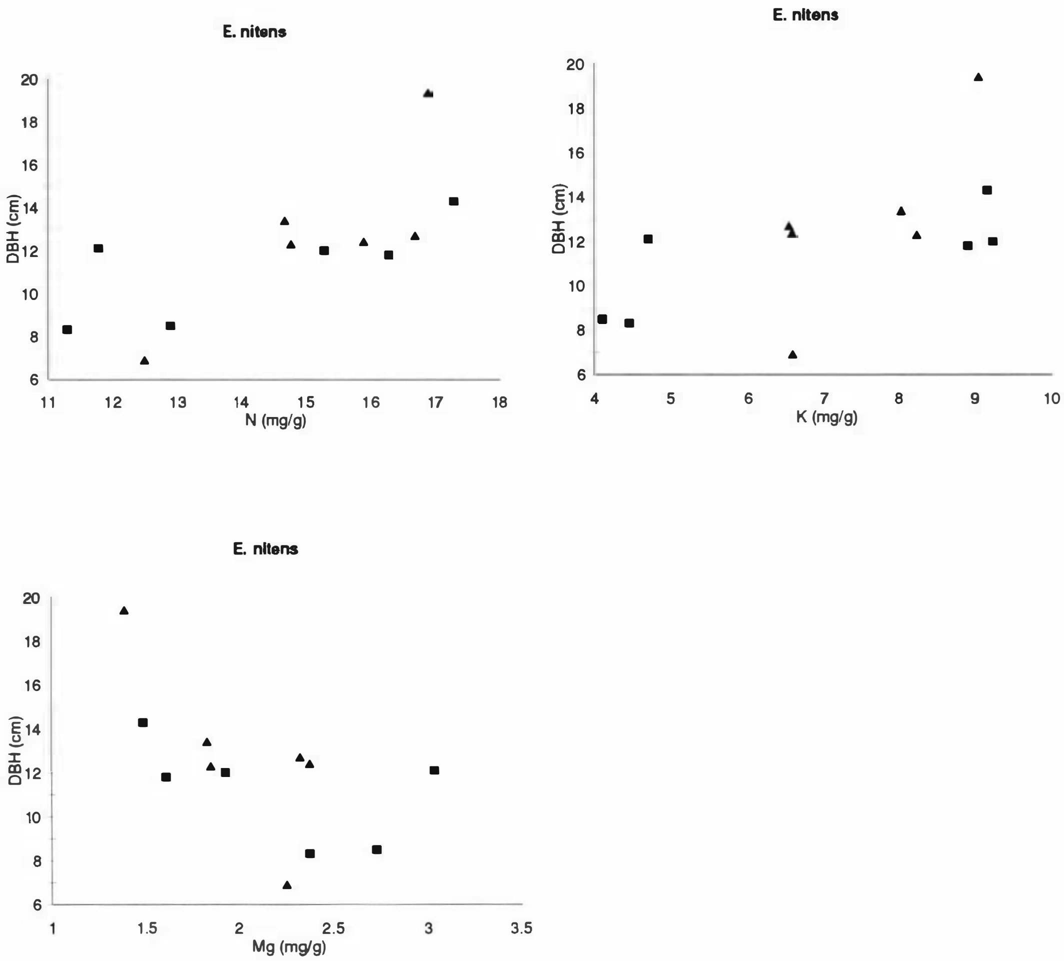


Figure 7.25 Scatterplots of the relationship between mean DBH (cm) and foliar nutrient concentration (mg/g DM) of N (top left), K (top right) and Mg (bottom) in *E. nitens* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

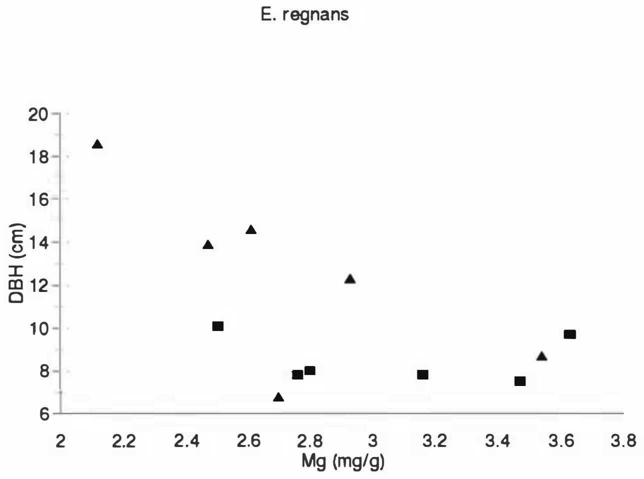


Figure 7.26 Scatterplot of the relationship between mean DBH (cm) and foliar nutrient concentration (mg/g DM) of Mg in *E. regnans* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

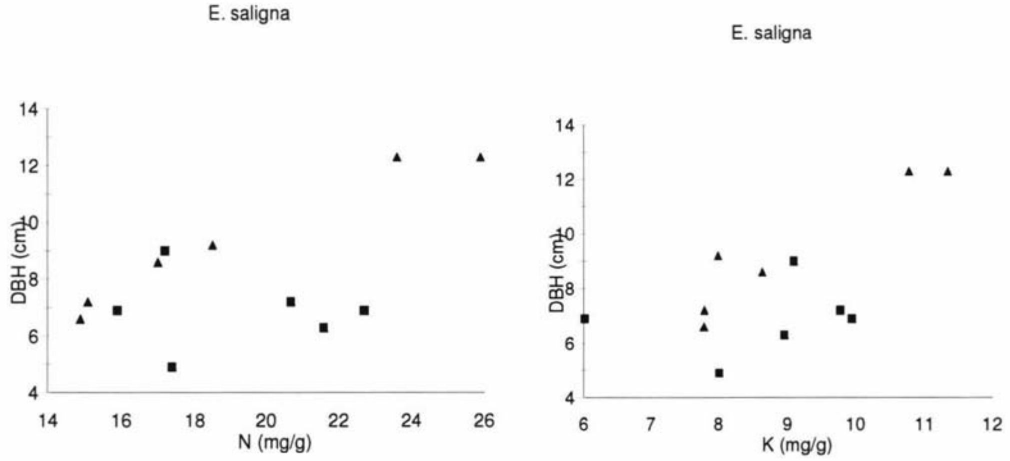


Figure 7.27 Scatterplots of the relationship between mean DBH (cm) and foliar nutrient concentration (mg/g DM) of N (top left) and K (top right) in *E. saligna* at age 5 years. Symbols: ▲ = sunny face, ■ = shady face.

7.7 Canonical correlation analysis of tree and environmental characteristics

7.7.1 Methods

Canonical correlation is a useful technique for analysing the correlation between sets of variables and may be considered an extension of multiple regression but, whereas in multiple regression there is a single dependent variable, in canonical correlation there is more than one (Afifi & Clarke 1996). In this case the dependent variables describe the performance of the trees, such as growth and form (dependent variables), and the independent variables describe the environmental factors, for example nutrients and topography.

The principal behind canonical correlation analysis is similar to principal component analysis (Chapter 6) but differs in that the objective is to maximise correlation rather than variance (Manly 1994). In canonical correlation analysis the objective is to find a linear combination, called a canonical variable, of the dependent (Equation 1) and the independent (equation 2) variables for which the selection of coefficients (a's and b's) maximises the correlation between the canonical variables. More than one set of canonical variables can be calculated for each set of variables, the maximum being equal to the number of variables in the smallest set of either the dependent or independent variables. The correlation between the first canonical variables for the dependent and independent variables is called the first canonical correlation. Other combinations of the variables, with selection of appropriate coefficients, allow calculation of additional canonical variables which are not correlated with previous canonical variables but where correlation with each other is maximised. This approach ensures that each pair of canonical variables measures a different aspect of each set of variables and that the correlation between any pair of canonical variables will be less than or equal to the preceding correlation (Afifi & Clarke 1996).

Equation 1 $\mathrm{CanY}_1 = a_1Y_1 + a_2Y_1 + a_nY_n$

Equation 2 $\mathrm{CanX}_1 = b_1X_1 + b_2X_1 + b_nX_n$

The independent variables utilised were the first three principal components of the foliage nutrient data (Chapter 6), slope angles and the TOPEX score (Chapter 4) of each plot. Principal components from the foliage nutrient data were utilised because there were strong correlations between some individual nutrients. Strong correlations among the dependent or independent variables can make interpretation of canonical variates very difficult, mostly because the number of possible linear combinations of the variables becomes infinite (Manly 1994). The first 3 principal components from the foliar nutrient PCA analysis (Chapter 6) were utilised for parsimonious reasons, accounting for almost 90% of the variation in foliage nutrients. Slope (Holland & Steyn 1975; Ares & Marlats 1995) and exposure (Thompson 1984) have been shown to influence growth in a number of tree species. The dependent variables were stem volume and stem form, expressed as the number of acceptable trees per plot at age 5 years after transformation (square root). Stem volume was utilised rather than DBH and height because they were strongly correlated (Section 7.4.5). Separate analyses were carried out for each subgenus, rather than with pooled data, to ensure that potentially important subgeneric differences were not obscured. The analysis was carried out with standardised variables to remove the effects of scale from the data using the PROC CANCORR procedure in SAS.

7.7.2 Canonical correlation

The first canonical correlations for both subgenera were moderately strong, 0.73 and 0.67 for *Monocalyptus* and *Symphyomyrtus* respectively (Table 7.28) as was the second canonical correlation for *Monocalyptus* (0.61), but the second canonical correlation for *Symphyomyrtus* was only moderate (0.49). The redundancy index shows that the canonical correlations in *Monocalyptus* have greater relevancy than in *Symphyomyrtus*, total redundancy being 0.46 (0.31 + 0.15) and 0.31 (0.20 + 0.11) respectively. The significance probabilities suggest that all correlations are highly significant. While significance tests for canonical correlations can be unreliable (Manly 1984) the probabilities in Table 7.28 are sufficiently low to allow confident rejection of the null hypothesis.

Table 7.28 Statistical characteristics of each pair of canonical variables for each subgenera. The redundancy index measures the proportion of the variation in the dependant canonical variable explained by the opposite independent canonical variate.

	Variable Number	Canonical correlation	Redundancy index	Significance
Monocalyptus				
	1	0.74	0.31	< 0.0001
	2	0.59	0.15	< 0.0001
Symphyomyrtus				
	1	0.66	0.20	< 0.0001
	2	0.45	0.11	0.015

7.7.2.1 First canonical correlation

The coefficients for the dependent variables and the correlations between the dependent variables and the first canonical variable are given in Table 7.29. This reveals that the first canonical variable for the dependent variables in *Monocalyptus* was mostly determined by stem volume. Both the coefficient and correlation were considerably greater than those of form. In contrast, the first canonical variable for the dependent variables in *Symphyomyrtus* mostly represented the number of acceptable stems per plot, the coefficient and correlation being considerably greater, though negative, than those for volume.

The first canonical variables for the independent variables for each subgenus also differed (Table 7.29). For *Monocalyptus* the first canonical variable was very strongly, negatively correlated with slope angle but with some positive influence from PC1, which represented foliar concentrations of N, P & K (Chapter 6). In *Symphyomyrtus* the first canonical variable for the independent variables was very strongly, positively correlated with PC1, but also with some negative influence from slope. The coefficients reinforce these interpretations.

The first canonical correlation in *Monocalyptus* therefore represents a negative relationship between stem volume and slope angle, plots on steep slopes producing trees with lower stem volume than those on gentle slopes. However in *Symphyomyrtus* the first canonical correlation indicated that the number of acceptable trees per plot was lower in plots with high foliar concentrations of N, P and K but higher in plots on steeper slopes.

Table 7.29 Standardised coefficients and correlations between the first canonical variables and the variables in the dependent and independent sets.

			Coefficient	Correlation
Monocalyptus				
	Dependent variables			
		Volume	0.93	0.98
		Acceptable trees	-0.20	-0.44
	Independent variables			
		PC1	0.37	0.64
		PC2	-0.04	-0.33
		PC3	0.01	-0.21
		Slope	-0.84	-0.93
		TOPEX	0.15	-0.20
Symphyomyrtus				
	Dependent variables			
		Volume	0.58	0.50
		Acceptable trees	-0.86	-0.81
	Independent variables			
		PC1	0.71	0.91
		PC2	-0.19	-0.10
		PC3	-0.14	-0.60
		Slope	-0.38	-0.78
		TOPEX	0.13	-0.38

7.7.2.2 Second canonical correlation

Interpretation of the second canonical variables for *Monocalyptus* appears to be relatively straightforward. The dependent canonical variable was strongly influenced by the number of acceptable trees per plot (Table 7.30) and the independent canonical variable is strongly influenced by TOPEX score, influence from the remaining variables being negligible. The second canonical correlation in *Monocalyptus* can therefore be summarised as a positive relationship between acceptable tree numbers per plot and stem volume, and reduced exposure, remembering that high TOPEX scores represent reduced exposure (Chapter 3).

In *Symphyomyrtus* the dependent canonical variable was mostly influenced by stem volume but also with a contribution from acceptable tree numbers. Trees with large volumes but poor form achieved a high value for the second canonical variable from the dependent variables. The independent canonical variable did not appear to be dominated by a single factor. The coefficients for slope and PC1 suggested that they were the most important variables, however the correlations between slope (-0.31) and PC1 (-0.38) and the second canonical variable were less than that for PC2 (-0.66), which was associated with foliar concentrations of Ca and Mg. TOPEX appears to be of less importance, in contrast to *Monocalyptus*. A possible interpretation of the second canonical correlation might be that in *Symphyomyrtus* plots large trees of good form were associated with low foliar concentrations of Ca and Mg but not necessarily high concentrations of N, P and K and were more likely to be found on lower slope angles.

Table 7.30 Standardised coefficients and correlations between the second canonical variables and the variables in the dependent and independent sets.

	Coefficient	Correlation
Monocalyptus		
Dependent variables		
Volume	0.45	0.20
Acceptable trees	1.01	0.90
Independent variables		
PC1	0.16	0.00
PC2	0.21	0.43
PC3	-0.01	-0.10
Slope	-0.17	0.14
TOPEX	0.97	0.96
Symphyomyrtus		
Dependent variables		
Volume	0.82	0.86
Acceptable trees	0.50	0.58
Independent variables		
PC1	-0.77	-0.38
PC2	-0.35	-0.66
PC3	-0.24	0.04
Slope	-1.0	-0.31
TOPEX	0.67	0.26

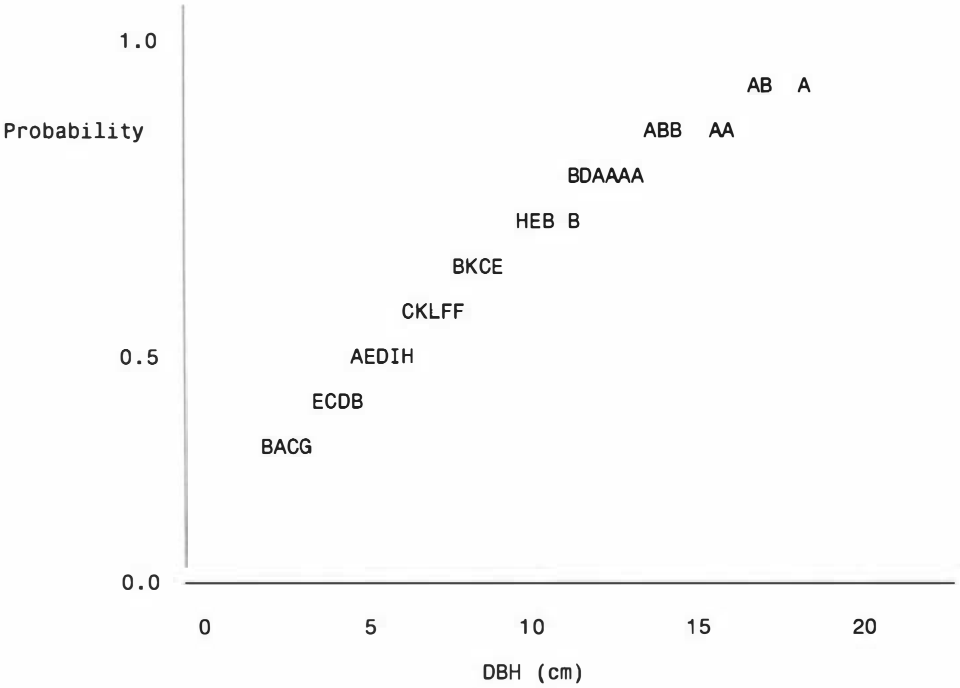
7.8 Interactions between growth and form and the incidence and severity of *Ophelimus eucalypti* (leaf gall) and possum browse damage in *E. botryoides* and *E. saligna*

7.8.1 Methods

Both *E. botryoides* and *E. saligna* suffered significant canopy damage from leaf gall and possum browse damage. Canopy damage from pests can influence height and diameter growth in many tree species (Gadgil et al 1995). The incidence of both pests was recorded with a simple scoring system at 3 and 4 years of age. At 5 years the scoring was extended slightly to include an assessment of severity if the pest was present. As this is categorical data, logistic regression was utilised to investigate the influence of possum browsing and gall infection on height and DBH in these species. The relationship between pest incidence and tree form was also investigated. Logistic regression enables the use of a binomial response variable, in this case, the presence or absence of a pest and utilises odd's ratios, the odds of an event occurring/the odds of an event not occurring, to model the probability of a dependent variable occurring in response to variation in independent variables (Afifi & Clarke 1996). The chi-square statistic (Steel & Torrie 1980), was used to assess the significance of logistic regressions. After the logistic regression analysis, predicted probabilities were estimated and subsequently utilised to graph the response of predicted probabilities to variation in the explanatory variable (below). The PROC LOGISTIC procedure in SAS was employed to conduct the analyses.

7.8.2 Logistic regression of possum browse incidence on DBH and height

Logistic regression analysis between possum browsing incidences at 3 and 4 years of age (trees with possum damage at either age scored 1, all other trees scored 0) and DBH ($P = 0.0007$) and height ($P = 0.007$) at age 5 years were highly significant. The probability of being browsed by possums increased with increasing DBH and height (Figure 7.28), the probability of large trees being browsed approaching 1.0, whereas the probability of being browsed was about 0.4 for the smallest trees.



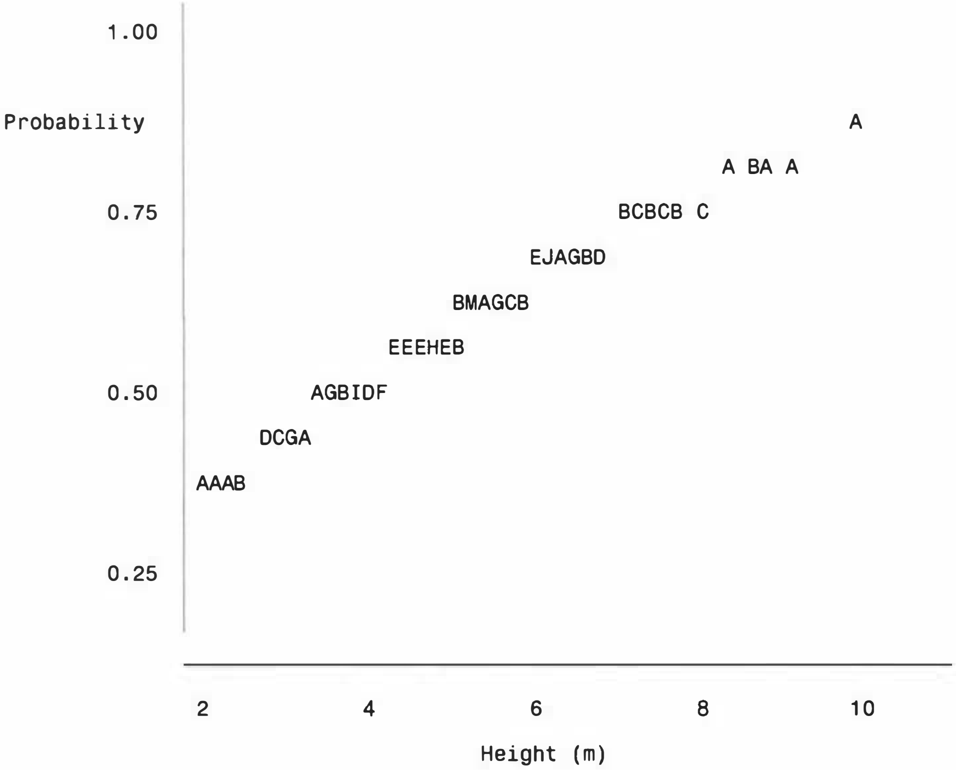
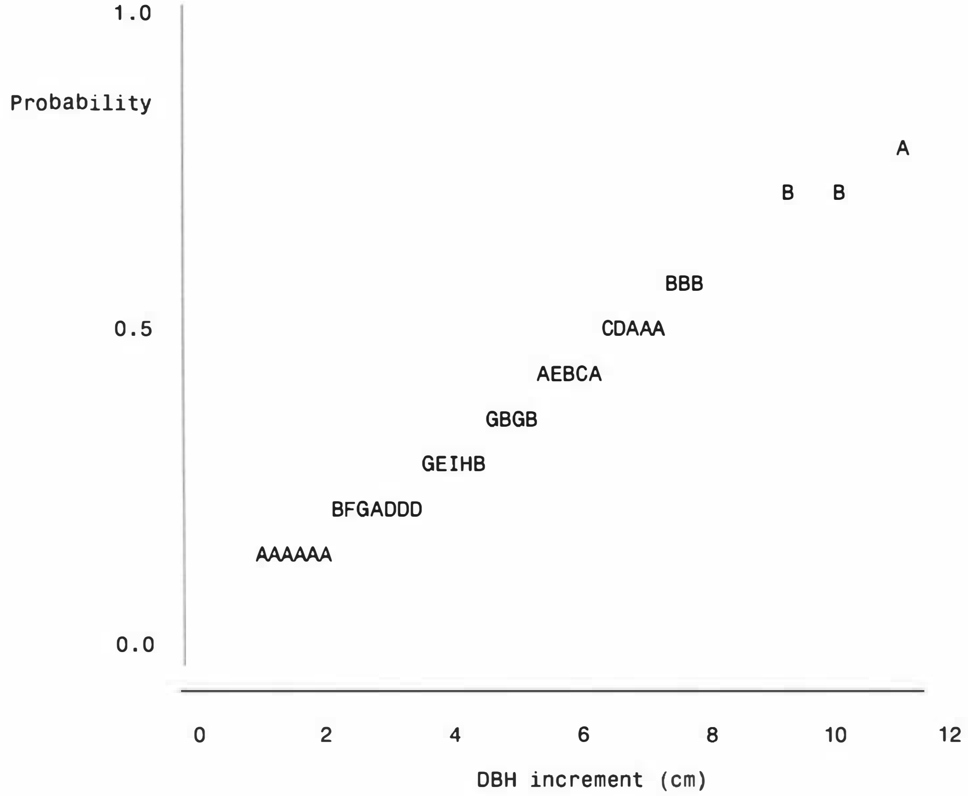


Figure 7.28 The influence of DBH (top) and height (bottom) at age 5 years on the probability of *E. botryoides* and *E. saligna* trees being browsed by possums in the previous two years. A = 1 observation, B = 2 etc.

7.8.3 Logistic regression of *Ophelimus eucalypti* incidence on DBH and height increment

When regressed against height and DBH at age 5 years the incidence of leaf gall infection at 3 and 4 years of age (any tree with leaf gall at either assessment time scored 1, all other trees scored 0) was not significant. However, when regressed against DBH and height increment between 3 and 5 years, gall infection at 3 and 4 years of age was found to be associated with both measures of growth ($P = 0.002$). The probability of being infected with leaf gall increased with increasing DBH and height increment, the fastest growing trees were more likely to be infected. (Figure 7.29). The probability of the fastest growing trees being infected was about 0.75 while the probability of infection in trees with small growth increments was only about 0.2.



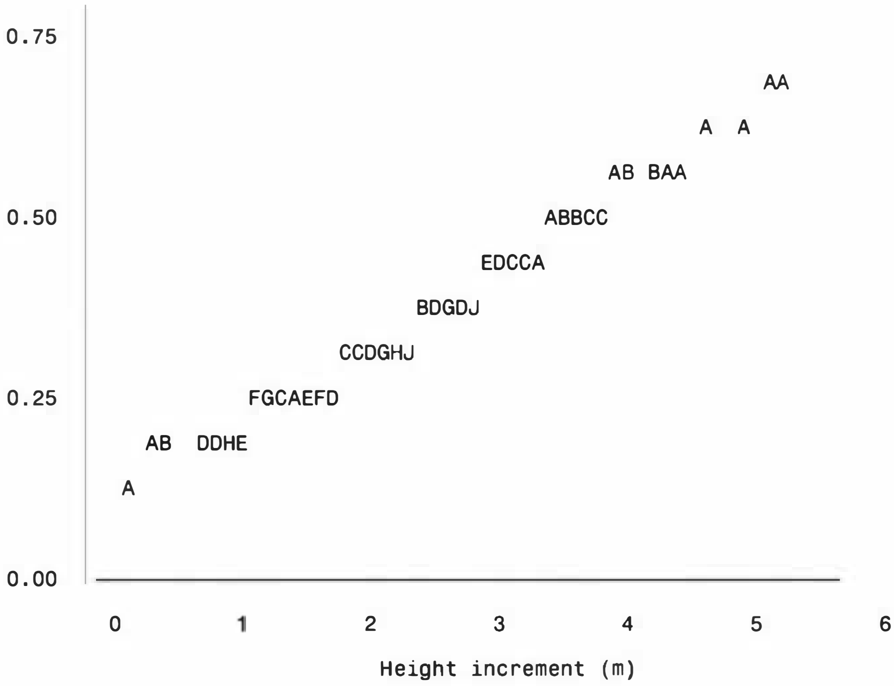


Figure 7.29 The influence of DBH (top) and height (bottom) increment between 3 and 5 years of age on the probability of *E. botryoides* and *E. saligna* trees being infected with *Ophelimus eucalypti* during that period. A = 1 observation, B = 2 etc.

7.8.4 Logistic regression of possum browse damage and *Ophelimus eucalypti* infection on tree form

The association between possum browse and tree form was also highly significant (P = 0.0001). Trees with a high form score (poor form) at age 5 years were very likely to have suffered possum damage during the previous two years (Figure 7.30), whereas the probability of the best trees being browsed was only 0.25. The regression between gall incidence and tree form was not significant. Trees with poor form were less likely to have been infected with leaf gall during the previous 2 years than trees with good form (Figure 7.31), but the probability of leaf gall changed little across a wide range of tree form scores.

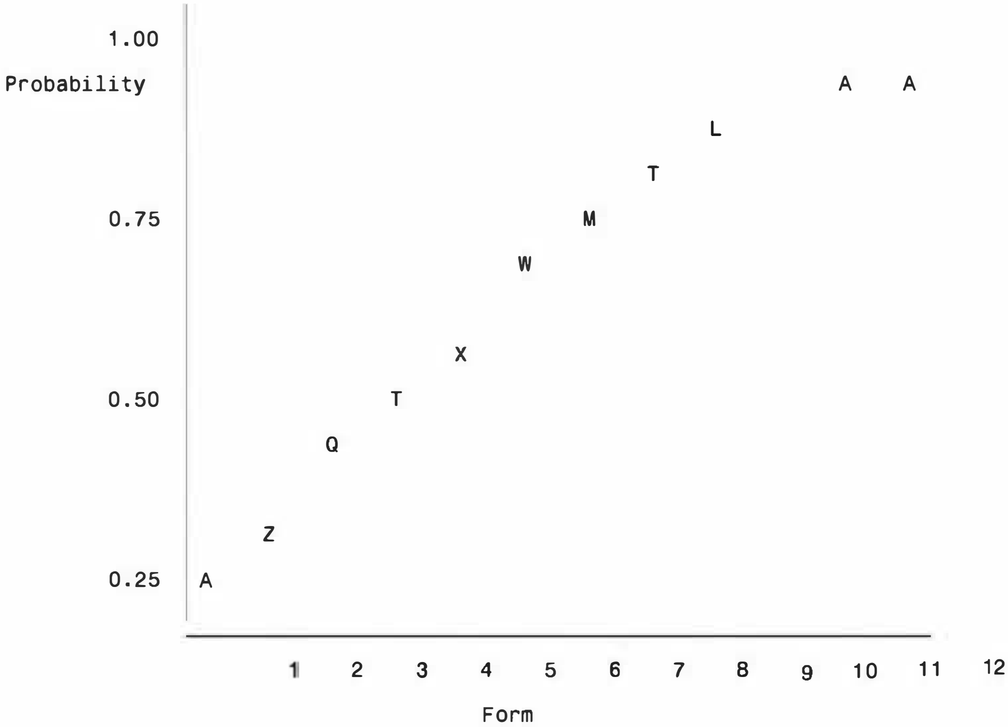


Figure 7.30 The probability of *E. botryoides* and *E. saligna* trees being browsed by possums versus tree form at age 5 years. A = 1 observation, B = 2 etc.

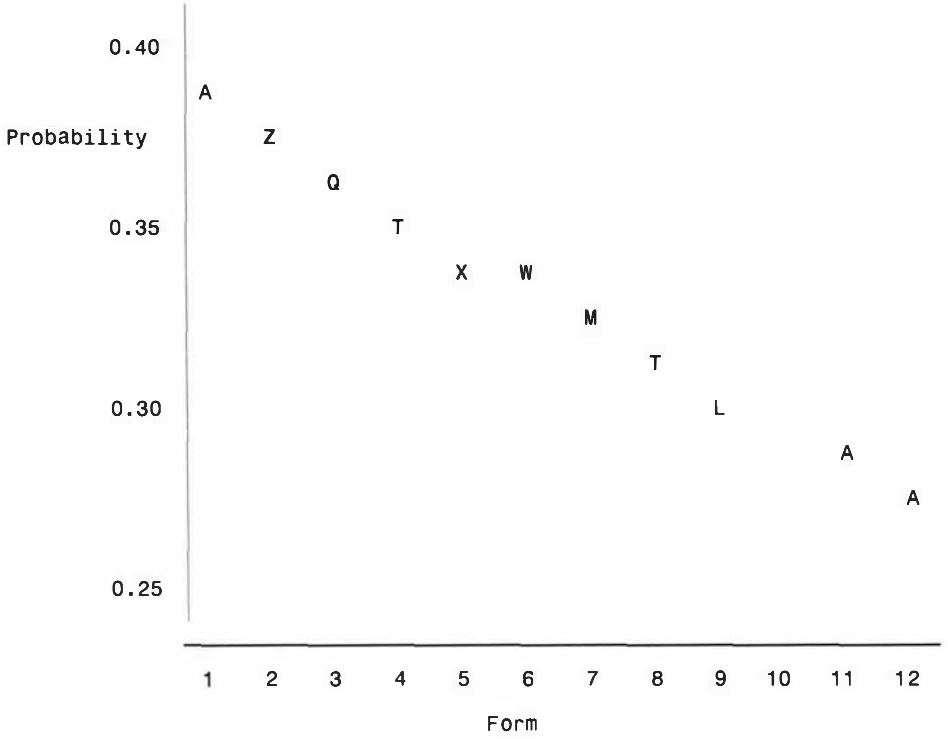


Figure 7.31 The probability of *E. botryoides* and *E. saligna* trees suffering *Ophelimus eucalypti* infection versus tree form at age 5 years. A = 1 observation, B = 2 etc.

7.8.5 The relationship between possum browse damage and *Ophelimus eucalypti* infection

To investigate the relationship between possum browse and leaf gall severity a cross tabulation technique was employed utilising the PROC FREQ procedure. Data consisted of severity scores allocated at the age 5 assessment. Scoring: No visible evidence of the pest = 0, moderate pest levels = 1 and high pest levels = 2. The PROC FREQ procedure is appropriate when both dependent and independent variables are categorical. It is similar to logistic regression in that it also utilises odd's ratios and association between the variables can be tested using the chi squared test (Afifi & Clark 1996). The frequency of cross tabulated scores for each pest was graphed (Figure 7.32).

The severity of leaf gall infection varied with the severity of possum browse damage. When the leaf gall score is = 0 or 1 the number of trees with severe possum browse damage (score = 2) was low. However when the leaf gall score = 2, the number of trees with severe possum damage was greater than no or moderate damage. Or, to look at the response of gall infection to possum browse damage severity, the greatest number of trees had no gall damage (between 20 and 25 trees) when possum damage severity was = 0 or 1, numbers declining in order as gall severity increased. The reverse occurred when possum damage was heavy (score = 2), tree numbers increasing with successive increases in gall severity. The chi-square test of general association between possum browse damage and leaf gall infection was highly significant (P = 0.004).

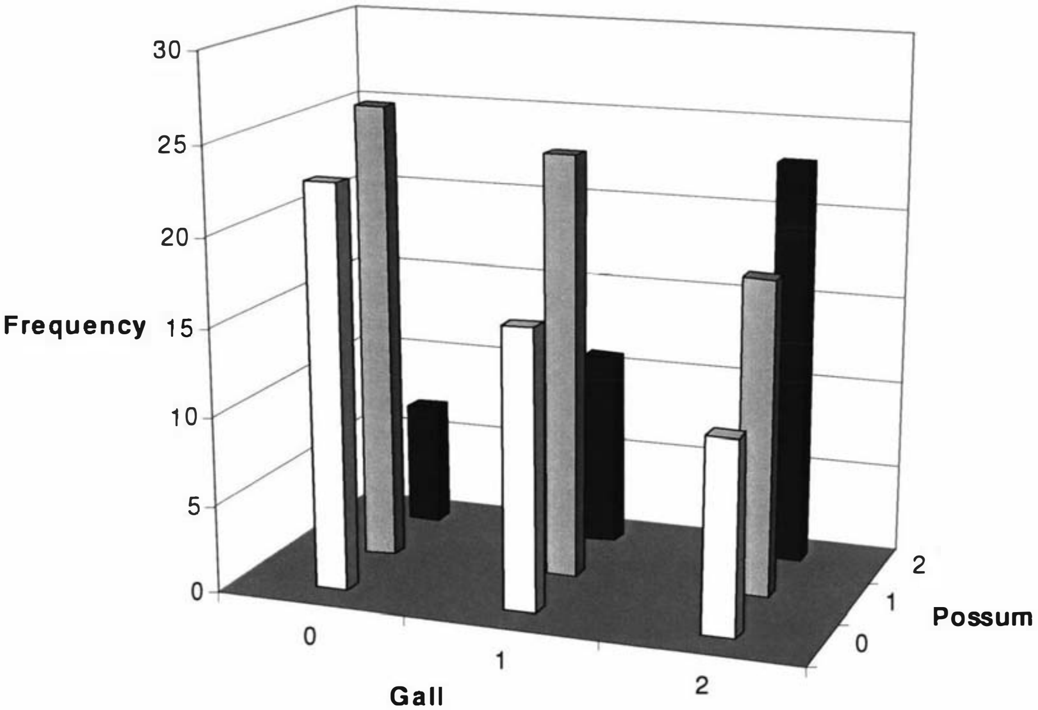


Figure 7.32 The association between possum browse and leaf gall severity. Scores: 0 = no damage, 1 = moderate damage and 2 = severe damage. Frequency = the number of trees in each category.

7.9 Discussion

Discussion of the results will include comparisons with other New Zealand and overseas research, when appropriate, on the influence of microclimate on the relative performance of different *Eucalyptus* species. Any interactions between microsite and species will be explored and an attempt made to explain these interactions including factors such as species characteristics, for example climatic adaption, microclimate environment and the influence of pests and diseases. Whenever appropriate the results from different sections will be linked, for example growth with pest and disease problems. Results which include analysis of relationships between growth and environmental factors introduced in earlier chapters, for example foliage nutrient concentrations, will also be discussed here. Otherwise, the final discussion (Chapter 9) will link results from different chapters.

7.9.1 Seasonal growth

Diameter and height growth were seasonal in all species, a reflection of seasonal differences in solar radiation and temperature (Chapter 4), typical of most regions of New Zealand. Seasonality of tree growth in New Zealand has been reported in native hardwood and exotic coniferous forest species including *P. radiata* (Baker 1988) as well as several eucalypt species including *E. fastigata*, *E. regnans* and *E. saligna* (McKenzie & Hay 1996; Hay et al 1999). The effects of aspect and slope position on both diameter and height growth can also be explained by seasonal differences in radiation and temperature. For example, diameter growth in the winter and spring was higher on the sunny face than on the shady in most species, a reflection of higher radiation and temperature during these seasons on the sunny face, while aspect differences in diameter and height generally declined over the summer in accordance with radiation and temperature differences. Temperature regimes on different aspects are ultimately driven by solar radiation (Burgess 1988).

While both diameter and height growth were seasonal, height growth appeared to be more seasonal than was diameter growth in most species, an exception being *E.*

cladocalyx. The relative contribution of winter growth was influenced by aspect. On the shady face the contribution to annual diameter and height growth was 9.2 and 7.8 % respectively, not significantly different. However on the sunny face the contribution of winter growth to annual diameter and height growth was 15.7 and 10.7%, respectively. This pattern has been recorded in eucalypts in Australia (Ankle & Webb 1975) and New Zealand (Hay et al 1999). Increased seasonality of height growth in eucalypts may be due to higher temperature thresholds for height growth compared to diameter (Cremer 1975). The similarity of the growth patterns on the shady face probably reflects the limitation of low radiation (Whitehead and Beadle 2004).

Seasonal DBH increments in 1998/99 were greatest in the spring, contributing between about 30 to 40% to annual diameter growth. Diameter growth declined in the summer with a further small decline in the autumn, but the decrease was the result of a substantial decline in diameter growth on the sunny face, diameter growth on the shady face being similar to or slightly better, in a few species, than spring growth rates (Figure 7.1b). Rainfall over the December 1998 to February 1999 period was below normal (Appendices 4 & 5) and the increased evapotranspiration characteristic of sunny faces (Lambert & Roberts 1976) suggests that moisture stress will have limited growth in that season (Whitehead and Beadle 2004). Height growth in the 1998/99 year was nonetheless greatest in the summer, contributing 50% or more of the annual growth in most species. This pattern of diameter and height growth suggests that temperature has a major influence on both height and diameter growth but that diameter growth is more vulnerable to moisture deficits (Hay et al 1999). These workers found that the pattern of seasonal diameter and height growth in three eucalypt species (*E. fastigata*, *E. regnans* and *E. saligna*) on central North Island Volcanic Plateau was similar to that of Tuapaka, diameter growth peaking in mid spring and height growth peaking in early summer. Optimal temperature for diameter growth in eucalypt species has been found to be similar to that for height growth, for example *E. nitens* (Shepherd et al 1976).

The trial site is subject to strong and persistent winds (Burgess 1988) which very probably had a negative effect on height growth, particularly on the most exposed microsites (Thompson 1984). Canonical correlation analysis suggested that TOPEX score was positively associated with volume growth, at least in *Monocalyptus* species (Section 7.7.2). The upper shady microsite was the most exposed microsite, mean TOPEX score being significantly lower (more exposed) than any other microsite (Table 7.31). The rate of tatter of flags on the shady face was also higher than flags on the sunny face. (Chapter 4). Evidence of a microsite effect on height growth can be seen in Figure 7.4a. Height growth during the spring of the 1998/99 year on the upper shady microsite was well below that of all other microsites. Wind can reduce height growth in trees through a number of different mechanisms ranging from mechanical damage, including breakage (McKenzie & Hay 1996), clustering of the leaf canopy, reducing the effective leaf area (Vogel 1989) to reduction of photosynthesis due to reduction of internal leaf temperature, particularly in strong winds (Dixon & Grace 1984).

Table 7.31 TOPEX scores for each microsite. Numbers in parentheses = SEM.

	TOPEX
Upper shady	56 (1.9)
Lower shady	106 (4.0)
Lower sunny	144 (4.0)
Upper sunny	99 (1.5)

Growth in all plants is ultimately dependent on photosynthetic rate which is closely associated with interception of solar radiation, eucalypts typically having a potentially high rate of photosynthesis when solar radiation is adequate and where other environmental factors such as moisture and nutrients are not limiting (Whitehead and Beadle 2004). Relative aspect differences in solar radiation were greatest during the winter months, for example in the June to August 1998 and June to August 1999 periods radiation on the sunny face was 16% and 40% higher than on the shady face, respectively. Relative aspect differences in both diameter (Figure 7.1d) and height (Figure 7.3d) growth were also highest in the winter period. Aspect differences in mean temperature were modest, being less than 0.8°C in all months in both years for which data were collected (Chapter 4), but greatest in the winter months. However, relatively small differences in mean temperature can significantly influence growth in eucalypts (Ashton 1975) but response does vary with species. Species adapted to coastal environments with less diurnal variation, for example *E. microcorys*, are likely to have a narrower temperature response curve for photosynthesis but a more rapid photosynthetic response to temperature, meaning that growth response to increasing temperature may be greater than in species with a broad temperature response curve (Battaglia et al 1996). Minimum temperature for growth has been estimated for some species, for example, Ashton (1975) found that the minimum mean temperature for growth in *E. regnans*, a southern high country species, was between 5 and 7.5°C. Mean winter temperatures at Tuapaka were above this range on the shady face (the coldest microsites) in all years for which temperature was measured (Appendices 1 to 3). Very low temperatures associated with high radiation can result in cold induced photoinhibition (Whitehead & Beadle 2004), but while a few frosts were recorded at Tuapaka, they were relatively light and confined to the winter period when radiation was also low and therefore very unlikely to have induced photoinhibition.

There were consistent and significant species differences in seasonal growth. *E. nitens* generally had the best height growth and was in the best group for diameter in all seasons apart from winter. This is not surprising as this species is noted for its relatively wide adaptability in New Zealand conditions compared to other eucalypts (Barr 1996). It is a high altitude species (Boland et al 1984) and the provenance used in the current study comes from the southern extent of its natural range, Central Victoria (Chapter 3). Conversely, *E. microcorys* was generally the poorest or among the poorest group in all seasons. The difference between these two species is probably the result of different optimum temperatures for growth. Species from southern latitudes usually have lower optimal temperature for growth than those from northern latitudes (Paton 1980). There were several examples of interactions involving species and season, one of the more notable involving *E. cladocalyx*. During the spring height growth in this species was intermediate, poor during the summer and again intermediate in the autumn. However in the winter *E. cladocalyx* had the best height growth (Figure 7.4d). Comparison of seasonal height growth increments shows that height growth in the winter was similar to that in the spring and autumn and only marginally less than that in summer. The end result of this is a relatively weak seasonal height growth response. A possible explanation for this is that *E. cladocalyx* is a South Australian species, adapted to hot, dry summers, 380-650 mm annual rainfall with a winter maximum, a Mediterranean climate (Boland et al 1984). Growth in tree species adapted to Mediterranean type climates is often poorly or negatively correlated with temperature but positively correlated with rainfall (Haston et al 1988; Stoneman et al 1995; Lara et al 2005), a strategy which minimises growth during the summer when drought risk is very high but allows growth to occur during the cooler months when moisture is less likely to be limiting. The seasonal response of diameter growth in *E. cladocalyx* was similar but appeared to have been affected by radiation, diameter growth on the shady aspect being less than that on the sunny aspect in the summer and winter. Reduced radiation will decrease diameter growth without necessarily reducing height growth in eucalypts, a strategy designed to help ensure that they emerge from shade (Florence 1996).

The eastern blue gums, particularly *E. botryoides*, performed poorly during the autumn and winter, especially height growth, which in some cases was negative (Appendix 9). This is probably due to possum browse damage from an early age (Section 7.4.8.2). Possum damage was mostly confined to the autumn and winter and breakage of leaders in the upper part of the canopy during these seasons (Plate 7.3) will have reduced the height of individual trees, and consequently, mean height growth.

Despite the general classification of eucalypts as shade intolerant there is some variation in the genus in tolerance of low light conditions (Florence 1996). For example, the distribution of *E. obliqua* has been shown to be associated with radiation (Kumar & Skidmore 2000), occurrence being greater in low radiation environments. *E. microcorys* is able to maintain height growth in relatively low radiation conditions (Kamis 1977 as cited by Florence 1996). Eucalypts tolerant of low light conditions have better growth under low radiation conditions than those not tolerant of low radiation (Florence 1996). None of the species in the current study showed consistently better growth on the shady aspect in all seasons.

7.9.2 Height and diameter

7.9.2.1 Microsite

There were significant aspect and slope position effects on DBH at age 5 years, DBH being greater on the sunny face and upper slope. The influence of aspect was greater than that of slope position. Height was also significantly affected by aspect at age 5 years but not by slope position. Mean aspect DBH and height on the sunny face were both 29% greater than on the shady. Aspect differences are a result of the higher growth rates on the sunny face, a consequence of higher radiation and temperature on this aspect for most of the year (Chapter 4). Aspect has been found to significantly influence growth in a number of tree species, including eucalypts, but the nature of the response is dependent on the local environment. For example the growth of two *Eucalyptus* species in Israel was found to be better on the shady face than the sunny (Brunori et al 1995), a result of low rainfall (mean annual rainfall 220 mm) and higher evapotranspiration on the sunny face, meaning that moisture stress on the sunny face was more limiting than on the shady. Moisture stress reduces solar radiation interception through a reduction of leaf area and leaf area duration (Pook 1985) and also reduces radiation conversion efficiency in eucalypts (Harrington & Fownes 1995). While soil moisture deficits in the hill country flanking the Tararua Range are possible, particularly on the sunny face, they are seasonal, and typically of short duration (Cowie 1978) and therefore less likely to significantly limit photosynthesis. Evidence that soil moisture was adequate for most of the year can be seen in the response of a drought sensitive species, *E. regnans* (Boland et al 1984; Florence 1996), height and diameter on the sunny face at age 5 years being greater than on the shady.

Height growth was not influenced by slope position whereas DBH was greater on the upper slope. This may be because height growth was limited by increased exposure to wind on the upper slope whereas diameter growth may be enhanced by wind, a strategy which results in increased resistance to the mechanical strains imposed by strong wind (Telewski 1995). Higher soil fertility, particularly N, on the upper shady microsite may have resulted in increased diameter growth relative to height growth. The DBH:height ratio was correlated with foliar N in four species (Table 7.26).

The combined effect of increased DBH and height on the sunny face resulted in mean stem volume on the shady face being 54% of that on the sunny face. The influence of slope position was less than this, reflecting the relatively small effect of slope position on DBH and the absence of any effect on height.

7.9.2.2 Species

There were significant differences in mean DBH and mean height in all years. *E. nitens* was the best species at all ages while *E. microcorys* was the poorest species at all ages. The slopes of the DBH and height versus age graphs (Figures 7.6 and 7.7) show that the difference between these species increased over time. This divergence also occurred among the remaining species, the ash's, *E. obliqua* and *E. regnans*, generally the best of these by age 5 years. However, two stringybark species, *E. baxteri* and *E. globoidea*, had similar DBH to the ash's at age 5 years.

The growth of eucalypt species which have been widely evaluated in New Zealand can be compared with performance at Tuapaka. For example, growth of a relatively site tolerant species, *E. nitens* (Miller et al 1992), at Tuapaka compares favourably with a number of other trials in both the South and North Islands and suggests that site quality at Tuapaka is moderately good, particularly on the sunny face. Wilcox (1985) found that the best *E. nitens* provenance (central Victoria) in Longwood Forest, Southland attained a mean DBH of 11.6 cm at 5 years of age on a site described as 'a good site for eucalypts'. This is almost identical to the mean DBH of 12.0 cm for this species at Tuapaka (Table 7.4). The provenance used at Tuapaka was also from central Victoria (Chapter 3). There was slight *Paropsis charybdis* damage in the Longwood trial which may have had a small effect on performance. Franklin (1980) assessed a number of *E. nitens* provenances at three sites on the West Coast of the South Island. At age 3 years the best provenance (central Victoria) had attained a mean DBH of 7.9 cm and mean height of 7.3 m at Slab Hut Creek, near Reefton, the best of the three sites. The equivalent performance at the poorest site, near Ahaura, was 3.2 cm and 3.5 m for DBH and height respectively, also a central Victorian provenance. Mean DBH and height of *E. nitens* at Tuapaka was intermediate to these sites at the same age.

Hathaway and King (1986) assessed the potential of a number of eucalypt species for erosion control in seasonally dry hill country in the Wairarapa. At the best site, Pakaraka, mean DBH and height of six *E. nitens* provenances at 5 years was 5.3 cm and 4.2 m respectively. At the poorest site, Kahuiti, mean DBH and height was 3.9 cm and 3.5 m respectively. Both sites had suffered extensive slip erosion in the years prior to planting. Nonetheless, growth at these sites was well below that at Tuapaka. Growth at Tuapaka was not as good as that at a Rotorua site (Longmile) assessed at four years of age; DBH and height being 16.2 cm and 10.5m respectively (Miller et al 1992).

The growth of the ash species was less than that of *E. nitens* but better than most other species at Tuapaka. There were no differences in height or DBH between *E. obliqua* and *E. regnans* at 5 years. Many New Zealand trials which have included both ash species have found that *E. regnans* is slightly better than *E. obliqua* (Wilcox et al 1985; Johnson & Wilcox 1989), despite the greater site tolerance of *E. obliqua* (Florence 1996), but it has performed better than *E. regnans* on some dry Hawke Bay sites (Shelbourne et al 2002). *E. obliqua* has greater drought tolerance (Boland et al 1984), but less frost resistance (Adams 1981; Johnson & Wilcox 1989) than *E. regnans*. The performance of *E. regnans* at Tuapaka was better than that at Longwood, Southland (Wilcox 1985), Pakaraka and Kahuiti in the Wairarapa (Hathaway and King 1986), but not as good as at Tokoroa (Wilcox 1982) also suggesting that Tuapaka is a good quality site.

The performance of the eastern blue gums at Tuapaka was generally poor. Mean DBH of *E. botryoides* at Tuapaka was similar to that at Pakaraka but better than at Kahuiti (Hathaway and King 1986), however height growth at Tuapaka was better than at both Wairarapa sites. Height and DBH of *E. saligna* at Rotoehu Forest in the Bay of Plenty was, respectively, 70.0% and 32.0% higher than at Tuapaka at a similar age (Hay et al 1999). The long term mean annual temperature at Rotoehu is 13.0ºC (New Zealand Meteorological Service 1983), similar to the mean annual temperatures recorded at Tuapaka (Chapter 4), suggesting that temperature was probably not a factor in the difference. The area planted in *E. botryoides* and *E. saligna* has probably been greater in Northland than in any other region of New Zealand (Barr 1996). Early growth of both species at Kaikohe, Northland was better than at Tuapaka (Low et al 1999), however caution is required when comparing performances from different time periods due to the recent arrival and establishment of insect pests which have been particularly severe on these species (Withers & Bain 2000; Withers et al 2000), including at Tuapaka.

There are fewer published accounts of the growth of stringybark eucalypts in New Zealand. Most are from Northland (Low et al 1999; Shelbourne et al 2000b) though Hathaway and King (1986) included several stringybark species in their evaluation of species suitable for erosion control in the Wairarapa. The performance of *E. agglomerata*, *E. globoidea* and *E. muelleriana* in the Wairarapa trials at 5 years was less than at Tuapaka, even on the shady face. Mean height at Tuapaka was 70%, 69% and 35% more than at the Pakaraka site in *E. agglomerata*, *E. globoidea* and *E. muelleriana* respectively. At Kahuiti, the poorest of the Wairarapa sites, mean height in these species ranged from about ⅓ to ½ those at Tuapaka. DBH differences were similar to those of height. Of the stringybark species *E. muelleriana* has been evaluated more than other species in New Zealand, mainly in the upper North Island. Shelbourne et al (2000b) reported on the performance of different *E. muelleriana* provenances at sites near Whakatane in the Bay of plenty and Whangarei, Northland. The Bay of Plenty site suffered severe frost damage with high death rates and was subsequently abandoned, highlighting the problem of frost sensitivity in many eucalypt species (Johnson & Wilcox 1989). At 6 years mean height and DBH (14.5 m and 20.0 cm respectively) at the Northland site were more than twice those at Tuapaka at 5 years (Shelbourne et al 2000b). Research on the remaining stringybark species included in the Tuapaka study, *E. baxteri* and *E. pilularis*, is very scarce. There is very little information on *E. baxteri* of any sort in New Zealand. *E. pilularis* has been planted in New Zealand, particularly in Northland (Barr 1996) but research information is limited.

E. cladocalyx has not been widely planted in New Zealand, but has performed well in Hawkes Bay (Barr 1980). It has rarely been included in scientific comparisons but Hathaway & King (1986) included it in their Wairarapa trials. It performed well at Pakaraka achieving a mean height and DBH at 5 years of 4.9 m and 6.6 cm respectively, making it one of the better performed species at that site, very similar to its performance at Tuapaka. Growth at Kahuiti at 5 years (mean height and DBH 2.8 m and 2.6 cm respectively) was poor. Apart from anecdotal reports from farm foresters' experience with *E. microcorys* (Barr 1996) there is very little information on the performance of this species in New Zealand.

Analysis of covariance of mean DBH and height at age 5 years and adjustment of means for the influence of possum browse damage during establishment resulted in mean DBH for aspects and some species being adjusted. Possum browsing had a minor effect on height. Browsing reduces diameter growth proportional to the degree of defoliation because of a reduction in leaf area (Bulinski & McArthur 1999). Repeated low level browsing has been found to reduce diameter growth more than a single intensive browsing event (Abbott et al 1993). Height growth is not affected to the same extent because trees preferentially allocate resources to height growth, diverting carbohydrates from other plant parts in an effort to replace lost canopy (Candy et al 1992), an adaption to competition in natural forests which helps minimise the risk of becoming suppressed by surrounding trees, increasing the probability of survival (Florence 1996). The residual influence of possum browsing on diameter 5 years after the damage highlights the importance of the establishment period for plantation forests and the potential economic impact of pests.

7.9.2.3 Relationship between diameter and height

The relationship between diameter and height is very sensitive to site, age and species. Coefficients for Petterson curves for individual species were similar but there were some significant differences between species, the best performing species, *E. nitens* having greater height than *E. microcorys*, the poorest species, at any DBH. There were also microsite differences, trees on the shady face, particularly the upper slope, having lower height than those on the sunny face at the same DBH. This may be due to greater exposure on the shady face compared with the sunny. Mean TOPEX score on the shady face was 77.3 while that on the sunny face was 121.3. TOPEX was also negatively, $r = -0.35$ ($P = 0.001$) and -0.27 ($P = 0.03$), for *Monocalyptus* and *Symphyomyrtus* respectively, but weakly correlated with DBH:height ratio, indicating that less exposed plots have had increased height growth relative to diameter. Shade can also differentially influence height and diameter growth, trees in low solar radiation environments often suffering reduced diameter growth but maintaining height growth (Florence 1996).

7.9.3 Stem form

There were significant microsite and species differences in stem form. The form of *E. nitens* was clearly superior to all other species. The good form of this species, particularly provenances from central Victoria, has been noted in several studies (Franklin 1980; Wilcox et al 1985; Shelbourne et al 2000a) though may be influenced by site factors such as insect damage (Johnson & Wilcox 1989).

The poorest form was seen in *E. botryoides*, almost certainly the result of possum damage during the autumn and winter periods (Table 7.19). Breakage of the leader was a typical outcome of this damage and resulted in a number of defects ranging from multiple stems, kinks and large diameter branches. Poor form, particularly multiple leaders, in plantation eucalypts in New Zealand (Wilcox et al 1985; Shelbourne et al 2000a) and Australia (Bulinski & McArthur 1999), has been attributed to possum damage. *E. botryoides* and *E. saligna* trees browsed by possums were much more likely to have poor form (Figure 7.31). Possum preference for *E. botryoides* and *E. saligna* compared with other species has also been reported in New Zealand (Shelbourne et al 2000a). This may be due to high foliar N concentrations (Burns et al 1998). *Eucalyptus* herbivores, including insects and possums (McArthur et al 2003), prefer foliage with high N concentrations. This appears to be a response to high concentrations of polyphenols, particularly tannins, lignin and sideroxylonal, a eucalypt toxin, in leaves with low N concentration (Burns et al 1998; McArthur et al 2003). Tannins strongly deter feeding by possums (Marsh et al 2003) probably by reducing their ability to digest proteins (Cork 1996). Thus when foliar N concentrations are low possums are unable to digest the proteins they require, deterring them from feeding. Tannins appear to be particularly important in *Monocalyptus* species (Marsh et al 2003) whereas in *Symphyomyrtus* species, formylated phloroglucinol compounds such as sideroxylonal are more important (Eschler et al 2000). Feeding deterrence may be the result of conditioned flavour aversion caused by *Eucalyptus* terpenes (Lawler et al 1999b) rather than the presence of the toxins themselves.

There was a strong interaction between species and microsite for form (Figure 7.13). Several species displayed very little variation in form across microsites, for example *E. cladocalyx* and *E. microcorys*, whereas others showed considerable variation, for example *E. agglomerata*, which had poorer form on the upper shady microsite than remaining microsites. This resulted in the number of acceptable trees/plot being similar on all microsites in *E. cladocalyx*; some variation in *E. microcorys* but much variation in *E. agglomerata*, for example. On the upper shady microsite there were almost no acceptable trees in this species. The stability of form and acceptable tree numbers in *E. cladocalyx* and *E. microcorys* indicates that they may be less affected by exposure than is *E. agglomerata. E. cladocalyx* is utilised for shelter belts in South Australia and Victoria (Boland et al 1984) where it is regarded as a wind tolerant species (Burke 1998). Similarly *E. microcorys* is regarded as a highly suitable shelter species in Queensland (Sun & Dickinson 1997). Hathaway & King (1986) assessed the wind resistance of *E. agglomerata* at two Wairarapa sites but found it to be reasonably wind resistant at both sites however wind resistance was not assessed at different slope positions.

Most species produced between about 1 and 1.5 acceptable trees/plot depending on microsite, or between 14 and 21% of trees planted (including blanked trees), suggesting selection ratios (initial/final stocking) of between 5 to 7. These ratios are well above those required for *P. radiata* seedlings (4) on fertile sites in New Zealand (Holden 1995) and probably reflect the lack of genetic improvement in most eucalypt species in New Zealand (Burdon & Miller 1995).

7.9.4 Basic density

There were significant species differences in basic wood density, those species noted for producing high density wood, .ie. the stringybarks as well as *E. microcorys* and *E. cladocalyx* (Boland et al 1984), having higher density than other species. In contrast, microsite had little influence on basic density, re-enforcing the strong genetic influence on this characteristic compared to the effect of environment or management (Hillis 1978; Hillis 1990). There were a few minor differences only between outerwood and innerwood density. Typically, wood density in eucalypts increases with radial distance (Harris & Young 1980) but the relatively young age of the trees in this comparison probably meant that radial variation had not developed.

The basic densities measured at Tuapaka were higher than those reported from other trials in New Zealand using whole tree sampling in *E. nitens*, *E. regnans* and *E. saligna* for trees less than 7 years old but less than in *E. globoidea*, *E. muelleriana* and *E. pilularis* in trees between 13 and 17 years (McKinley et al 2000). Densities measured by whole tree sampling are generally higher than those measured from breast height cores because wood density generally increases above about 10% of tree height (Harris & Young 1980; Lausberg et al 1996). However, Shelbourne et al (2000a) reported basic densities in young trees (7-11 years) of several species which were higher than those at Tuapaka. Site variation in basic wood density may be due to the use of different provenances at different sites (Harris & Young 1980). Basic wood density increases with age in most eucalypt species but because of the limited data base in New Zealand the relationship is not clear (McKinley et al 2000). However, basic density in more mature trees is well above those at Tuapaka. For example, Haslett (1990) reported mean basic densities of 635, 550 and 585 kg/m^3 for *E. globoidea*, *E. muelleriana* and *E. pilularis* respectively whereas at Tuapaka the basic density of these species was less than 500 kg/m^3. Basic densities of New Zealand grown eucalypts are typically less than those from Australia (Boland et al 1984; Haslett 1990), probably because New Zealand eucalypts are relatively young compared to those harvested from natural forests in Australia. Low density (< about 460 kg/m^3) in New Zealand grown eucalypts has been associated with greater risk of serious internal checking (Harris & Young 1980).

Basic density was not associated with diameter in most species. In some softwood species, for example *P. radiata*, increased diameter is negatively associated with density (Maclaren 1993). This results from higher early wood content in fast growing trees which has much lower density (~ 300kg/m^3) than latewood (~ 600kg/m^3) (Harris & Cown 1991). However, in eucalypts early wood and late wood density is similar (Hillis 1990), consequently density is usually not associated with diameter growth (Shelbourne et al 2000b; Miranda et al 2001). The significant positive correlation between DBH at age 5 and density at age 5 in *E. muelleriana* contrasts with the results of Shelbourne et al (2000b) for 6 year old trees however their correlation was based on family means rather than individual trees within a family or provenance. Downes et al (1997) reviewed the relationship between DBH and basic density in eucalypts. They found that in most studies there was no correlation between DBH and density but that some studies produced positive correlations while others produced negative correlations. However, none of the studies included stringybark species.

The relationship between basic density in 5 year old trees at Tuapaka and 24 year old trees in the Wairarapa will be discussed in the final discussion (Chapter 8).

7.9.5 Pests

Apart from possum damage during establishment, tree health was generally good, most species being free of significant pest and disease damage. Some losses in the ash species, *E. obliqua* and *E. regnans*, were associated with *Fusarium* root infection. These are both *Monocalyptus* species which are less tolerant of wet soils and more vulnerable to root infections by pathogenic fungi including *Fusarium* compared to *Symphyomyrtus* (Noble 1989). At Tuapaka losses were more apparent in wet areas and often resulted in trees being windthrown.

Significant pest damage occurred in two species, the eastern blue gums, *E. botryoides* and *E. saligna*, as a result of infection by the leaf gall wasp (*Ophelimus eucalypti*) and canopy damage resulting from possum browsing. *Eucalyptus* leaf gall is a new pest of eucalypt trees in New Zealand (Chapter 2). Heavy infestation may result in tree death because of severe defoliation as a result of infected leaves being shed (Nicholas & Hay 1990). At the time of the final assessment at age 5 years a number of trees of both species, particularly *E. saligna*, had not shown any sign of infection, indicating that individual trees may have genetic resistance to leaf gall. Withers et al (2000) found that trees from a provenance of *E. botryoides* did not become infected in a planned comparison.

The probability of *E. botryoides* and *E. saligna* trees being browsed by possums at Tuapaka was greater for large diameter trees and, to a lesser extent, tall trees (Figure 7.28), which are more likely to have higher foliar N concentrations. Similarly the probability of trees with large growth increments between 3 and 5 years of age being infected with leaf gall was also high. The correlation between plot mean foliar N concentration and mean DBH at 5 years of age was 0.53 ($P = 0.007$). The correlation between foliar N concentration and height at age 5 was not significant however this may have been because possum damage reduced height through leader breakage (Wilcox et al 1985), masking any association. Removing the confounding influence of possum browsing and any effect of exposure (TOPEX) (Evans 1980) on growth through partial correlation analysis (Steel & Torrie 1980) greatly improved the correlation between foliar N concentration and growth indices (Table 7.32). Figure 7.32 indicates that leaf gall wasps and possums share a preference for the same trees, those with better growth or those with higher foliar N concentrations. Both pests appear to have been deterred from feeding on trees with low foliar N concentrations probably because these trees contained greater concentrations of antagonistic factors (Section 7.9.3). Logic suggests that trees with significant possum damage would not be able to be utilised by adult *Ophelimus* wasps because the young leaves required would have been consumed by the possums. However, Withers et al (2000) found that peak wasp emergence occurred in August and December, adults living for 10 days only. Appearance of new galls would mostly occur after these peaks. Consequently, new leaves produced during late summer and autumn are less likely to have galls and available for possums to browse, thus trees may show high levels of both pests. Galls undergo senescence with age (Withers et al 2000) suggesting that leaves carrying large numbers of galls would be less palatable to possums.

Table 7.32 Pearson correlation coefficients between foliar N concentrations in *E. botryoides* and *E. saligna* and height (m) and DBH (cm) at age 5 years, and, height and diameter increments between 3 and 5 years.

	DBH	Height	DBH Increment	Height Increment
	0.70**	0.59*	0.60*	0.51*

** P < 0.001, * P < 0.015

7.9.6 Correlations between foliar nutrient concentrations and growth

Foliar nutrient concentrations were correlated with height and DBH at age 5. Significant positive correlations between growth (DBH) and nutrient concentrations were mostly limited to N and occurred mostly in *Symphyomyrtus* species. Significant correlations between DBH and foliar N concentration were limited to the *Symphyomyrtus* species, *E. microcorys*, *E. nitens* and *E. saligna*; *Monocalyptus* species with positive nutrient-growth correlations included *E. muelleriana* (K) and *E. agglomerata* (P). However, the correlation between N and DBH was relatively weak in *E. microcorys* and *E. saligna*. *Symphyomyrtus* species are naturally found on more fertile soils (particularly N and P) than *Monocalyptus* (Noble 1989; Florence 1996) and have more rapid early growth (Davidson & Reid 1980) suggesting that, initially at least, their nutrient requirements are greater. However, species adapted to low fertility may have reduced ability to utilise additional nutrients (Grime & Hunt 1975). The strength of the correlation between N and DBH in *E. nitens* may be the result of the relatively good adaption of this species to the Tuapaka environment. Responses to increased nutrient supply are generally better in the absence of other growth constraints, for example moisture and soil texture (Judd et al 1996b).

The negative correlations between Ca and Mg and growth, and the positive correlations between N and DBH in *E. microcorys*, *E. nitens* and *E. saligna* may be the result of microsite effects. Foliar concentrations of Ca and Mg were highest on the lower shady microsite, conversely N (and K) concentrations were lowest on this microsite. Poor growth on the lower shady microsite will therefore tend to produce a positive correlation with N but negative correlations with Ca and Mg. Poor growth may have been due to low N but it may also have been the result of other microsite factors, principally low radiation and temperature. Stratifying the data into aspects and examining the correlations between N and DBH in *E. nitens* resulted in correlations between foliar N concentration and DBH of 0.74 (P = 0.09) and 0.82 (P = 0.045) for the shady and sunny faces respectively. This indicates that N was limiting diameter growth in this species. Similarly, the correlation between N and DBH in *E. saligna* on the sunny face was 0.98 (P = 0.006) but there were no significant correlations between N and DBH in *E. microcorys* after stratification. It is also possible that negative correlations between Ca and Mg and growth are the result of negative correlations between N and K and Ca and/or Mg in most species (Chapter 6). This is consistent with previous studies with eucalypts (Bell and Ward 1984) and may be due to reduced dilution of these nutrients when N concentration is lower (Grove 1990) and/or increased uptake of Ca and Mg when K levels are low in order to maintain osmotic and ionic potential (Dell et al 1995). It is difficult to isolate individual factors in field studies where, for example, soil factors, solar radiation and temperature may all vary conjointly (Pyrke & Kirkpatrick 1994). Canonical correlation was used to help identify some of the complex relationships between environmental factors and tree performance and the results of this are discussed later.

The positive correlation between N concentration and DBH suggests that N nutrition may have been sub optimal in some species, particularly *E. nitens* and *E. saligna*. Applications of fertiliser at or shortly after planting, particularly N, are standard practice in New Zealand (Knight & Nicholas 1996). The estimated response to an application of 60 g of urea (46% N) at planting on the central North Island Volcanic Plateau was 1.4 m and 2.0 cm additional height and DBH respectively at age 4 years (Poole & Fry 1980). The response to fertiliser applications at planting is dependent on the supply of nutrients available in the soil. In South Africa, for example, the probability of a response to N and P fertiliser has been linked to soil organic matter content. Applications of N may range from 25 g N/tree when soil C content is < 3.0% to no N when soil C content reaches about 10.0% (Herbert 1996). Soil C content at

Tuapaka ranged from 5.4 to 8.2% on different microsites (Chapter 3). N application at Tuapaka produced a strong visual response. Leaf N concentration is positively correlated with leaf area and net photosynthesis per unit leaf area in many tree species (Stewart et al 1980), including eucalypts (Cromer 1996; Anderson et al 2000).

Additional fertiliser applications (to establishment period) may also be feasible in some situations. In New Zealand broadcast applications of 250 kg/ha of urea at the beginning of the second spring have been estimated to increase height and DBH by 0.5m and 1.4 cm respectively in *E. regnans* (Poole & Fry 1980). Knight & Nicholas (1996) reported height increments after one year of up to 0.95 m from applications of up to 60 g of N to *E. regnans* seedlings at establishment, also on the Volcanic Plateau. Additional applications of N in the third and fourth growing seasons have also produced good growth responses (height and DBH) in New Zealand (Poole & Fry 1980). These results highlight the potential responsiveness of plantation eucalypts to N where environmental conditions are favourable, particularly soil moisture (Herbert 1996; Knight & Nicholas 1996). The probability of an economic response to fertiliser applications to young eucalypt plantations can be assessed through the use of foliar analysis (Chapter 6). Comparison of nutrient concentrations with critical or normal concentrations provides forest managers with a basis for such decisions (Dell et al 1995). For the limited number of species for which such information is available in New Zealand, foliar N concentrations at Tuapaka were generally low (Knight & Nicholas 1996).

Research on the response of plantation eucalypts to fertiliser application has largely been confined to *Symphyomyrtus* species because they are far more important as plantation species than are *Monocalyptus* (Florence 1996), a result of their rapid early growth (Noble 1989), a key attribute for pulp plantations. Consequently, there is very little information on the response of *Monocalyptus* species to fertiliser and critical nutrient concentrations, a notable exception being *E. regnans* which has been utilised as a plantation species in New Zealand (Knight & Nicholas 1996).

7.9.7 Root structure

A small study comparing the lateral root structure of two species, *E. nitens* and *E. saligna* on the shady and sunny aspects found that lateral root distribution was generally good with most trees having strong laterals in 3 or 4 quadrants, reducing the probability of toppling (Mason 1985; Coxe & Mead 1999). Seedlings were produced in root trainers which may help reduce distortion of roots during planting (Forest Research Institute 1999). There was some evidence of microsite influence on root structure. Trees on the shady face allocated more resources to a smaller number of large roots compared to the sunny face. This strategy may not necessarily result in increased susceptibility to windthrow provided that lateral roots are evenly distributed (Nicoll et al 1995). There were no aspect effects on lateral root score at Tuapaka. It is possible that because trees on the shady face are more resource limited than those on the sunny face, a smaller proportion of biomass is allocated to root growth (Stoneman & Dell 1993). The ability of tree roots to resist forces such as gravity and wind is partially dependent on their stiffness, which is proportional to the fourth power of root diameter (Coutts 1983). Trees on the shady face may have allocated a greater proportion of biomass to a smaller number of lateral roots in order to maintain the ability of these roots to resist distortion.

7.9.8 Relationships between environmental factors and tree performance

Canonical correlation analysis was used to investigate the relationships between environmental factors and stem volume production and form. Separate analyses were run for each subgenera. In *Monocalyptus*, the first canonical variable of the dependent factors was highly associated with stem volume and for the independent factors, primarily with slope angle. High slope angles resulted in lower stem volumes at age 5 years. Poor tree growth associated with steep slopes has been found in New Zealand (Hathaway & King 1986) and overseas (Ares & Marlats 1995). Steep slopes may have thinner topsoil (McIntosh et al 1981; Saggar et al 1999) often as a result of erosion (Trustrum & De Rose 1987) resulting in lower organic matter content and lower fertility (Lambert et al 2000) than moderate or gentle slopes. Soil moisture is usually lower on steep slopes because of lower organic matter content but also because runoff is greater and infiltration lower on steep slopes and (De Rose et al 1995). All of these effects can reduce growth in eucalypts (Florence 1996). At Tuapaka steep slopes had lower fertility than moderate slopes; the correlation between slope angle and mean foliar nutrient concentrations was negative for N, P and K but positive for Ca and Mg (Table 7.33). However, lower soil moisture content on steep slopes, particularly on the sunny face (Lambert 1977) will also have limited growth, particularly diameter. *Monocalyptus* are less responsive to nutrient supply than *Symphyomyrtus* but more sensitive to moisture stress (Noble 1989) suggesting that the reduction in stem volume associated with steep slopes was due to reduced soil moisture.

Table 7.33 Pearson correlation coefficients between slope angle (°) and mean foliar nutrient concentrations (mg/g DM) at Tuapaka.

N	P	K	Ca	Mg
-0.71**	-0.41*	-0.64**	0.50*	0.55*

** $P < 0.001$, * $P < 0.05$

In *Symphyomyrtus* the first canonical variable for the independent variables was associated with foliar nutrient concentrations (N, P and K) and to a lesser extent slope, while the canonical variable for the dependent variables was associated with the number of acceptable stems per plot and to a lesser extent stem volume. Higher foliar N P K concentrations resulted in poorer form. Assessment of form in eucalypts in New Zealand has primarily been associated with species and provenance comparisons (Franklin 1980; Wilcox et al 1985; Hathaway & King 1986; Johnson & Wilcox 1989; Shelbourne et al 2000a) while form is generally of little concern in other countries because eucalypt plantations are grown for pulp wood production rather than saw logs (Florence 1996). High fertility, particularly N, has a deleterious impact on form in *P. radiata* in New Zealand, a result of increased toppling, large diameter branches and other stem defects (Forest Research Institute 1991).

The second canonical correlation in *Monocalyptus* represented a positive association between TOPEX and form. *Monocalyptus* trees in more exposed plots had poor form compared to those in more sheltered positions whereas in *Symphyomyrtus* poor form was associated with high foliar concentrations of N P K, perhaps suggesting that *Monocalyptus* species are more vulnerable to poor form when planted in exposed positions. Several *Monocalyptus* species (*E. globoidea*, *E. muelleriana* and *E. pilularis*) have been noted for their poor form (Barr 1996; Shelbourne et al 2003), particularly when initial stocking is low (Barr 1996). Low initial stocking reduces mutual shelter and competition for light. Exposed plots are much more likely to be on upper slope positions where both exposure and solar radiation are greater. Several *Symphyomyrtus* species at Tuapaka, including *E. cladocalyx* and *E. nitens* are quite tolerant of exposure and showed very little variation in form on different microsites (Section 7.9.3) whereas form was poorest on more exposed microsites in several *Monocalyptus* species. Interpretation of the second canonical correlation in *Symphyomyrtus* is more problematic. It probably represents a negative association between foliar Ca and Mg concentrations and volume and a positive association between TOPEX and form and volume. Higher foliar N P K concentrations also appear to have had a negative influence on volume and form. The first canonical correlation in *Symphyomyrtus* represented a negative association between N P K concentrations and form and the second canonical correlation may in part reinforce this association.

7.10 Summary

Growth was significantly influenced by microsite and species at age 5 years. *E. nitens* was the most productive species having the best height (7.4 m), DBH (12.0 cm) and stem volume (48.9 dm^3). The ash species also performed well. The poorest species were *E. cladocalyx* and *E. microcorys*, a sub tropical species not well adapted to the relatively cool temperatures at Tuapaka, with the stringybark species being intermediate. Height and DBH at age 5 years on the sunny aspect was significantly better than on the shady in all species. Slope position had no influence on height growth but did influence DBH, which was lower on lower slope positions. The relationship between DBH and height was influenced by microsite, trees on the shady face had lower height than those on the sunny face at the same DBH.

Height and diameter growth were both strongly seasonal, reflecting the seasonality of solar radiation and temperature; diameter growth was highest in the spring while height growth was highest in the summer, in most species. Height and diameter growth were least in the winter. There were some species differences in the seasonal pattern of height and diameter growth. For example *E. cladocalyx* displayed a Mediterranean growth pattern, having relatively good winter growth and poor summer growth, an adaption to the climate in its native range. Aspect also influenced seasonal growth patterns. Diameter and height growth on the shady face was similar to that on the sunny face during the summer, however in the winter growth on the shady face was typically lower than on the sunny. Slope position also influenced height growth, particularly in the winter, growth on the lower slope being less than on the upper.

Basic wood density was strongly influenced by species, ranging from 400 to 598 kg/m^3, but the influence of microsite was small, highlighting the strong genetic influence on this trait. Density was lowest in *E. nitens*, *E. obliqua* and *E. regnans* and highest in *E. cladocalyx* and *E. microcorys* while the stringybark species were intermediate. Basic wood density at Tuapaka was significantly correlated with density in 24 year old trees of the same species growing in the Wairarapa.

There were significant differences between species in tree form but microsite had a minor influence only. Form in *E. nitens* was generally very good, better than all other species. On the other hand many *E. botryoides* trees had very poor form, probably because of possum damage. Common faults included multiple leaders and sweep. However, most species produced at least 1 tree/plot which would be acceptable as final crop.

Although a number of insect and vertebrate pests and fungal diseases were recorded only two caused significant damage; possums - a traditional pest, and a leaf gall caused by *Ophelimus eucalypti* - a relatively recent arrival in New Zealand. Possum damage was mostly confined to *E. botryoides* and *E. saligna* while leaf gall only affected these species. Both pests appeared to prefer well grown trees, probably because these trees had higher foliar N content and lower concentrations of polyphenols such as tannins.

Lateral root scores of trees excavated at age 6 years were generally low, indicating potentially good stability. There was some evidence that microsite influenced root structure. Trees on the shady face appeared to allocate more biomass to a smaller number of lateral roots than those on the sunny face.

The relationship between growth and form was investigated initially with correlation analysis of foliar nutrient concentrations (Chapter 6) with DBH and height at age 5 and subsequently with canonical correlation, which allows multiple dependent (stem volume, and form) and independent (foliar nutrients, slope angle and exposure) factors. In most species there were no positive correlations between foliar nutrient concentrations and growth. However, DBH was positively correlated with N in three species, all *Symphyomyrtus* but height was not correlated with N in any species. Foliar Mg was negatively corelated with DBH and/or height in four species. In *Symphyomyrtus* species high N P K concentrations were associated with poor form whereas in *Monocalyptus* foliar nutrients were not strongly associated with form or volume. Form was associated with exposure in *Monocalyptus*, exposed trees having poorer form than more sheltered ones. Volume in *Monocalyptus* was associated with slope angle, steeper slopes producing less volume, probably because of lower soil moisture in some seasons.

Chapter 8

Relationship between solar radiation and seasonal growth

8.1 Introduction

Plant growth, including trees, is ultimately dependent on the assimilation of carbon dioxide using energy acquired from the interception of solar radiation. The ability to intercept and utilise solar radiation is heavily influenced by environmental factors such as moisture. While radiation interception was not measured daily global solar radiation (Chapter 4) and seasonal growth (Chapter 7) were recorded. The relationships between seasonal radiation, rainfall, windrun, and height and diameter growth will be investigated.

8.2 Methodology

The seasonal mean daily solar radiation recorded on the shady and sunny faces between June 1997 and June 1999 but equipment failure on the sunny face meant that radiation was only measured from June 1997 to August 1998. Consequently, sunny face radiation over this period was estimated from the regressions between radiation on the shady and sunny face for individual seasons (Table 8.1) during 1997/98 (Chapter 4).

The relationship between seasonal mean daily radiation and growth was initially explored with the use of scatterplots of seasonal radiation and growth increments for each aspect. Regression analysis showed that the relationship between radiation and growth was not influenced by aspect, consequently aspects were combined. Species were plotted separately. The influence of seasonal rainfall and seasonal mean daily windrun on growth was also tested using multiple regression. Rainfall and windrun data recorded at AgResearch, Palmerston North was used for this purpose.

Table 8.1 The regressions between global solar radiation (MJ/m^2) on the shady and sunny face for each season during 1997/98. Numbers in parentheses = SE of slope.

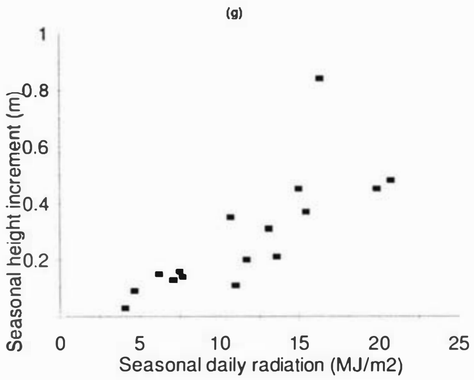
	Intercept	Slope	R^2
Spring	0.87	1.04 (0.05)	0.86
Summer	1.66	0.95 (0.07)	0.66
Autumn	0.13	1.40 (0.06)	0.86
Winter	0.20	1.48 (0.11)	0.68

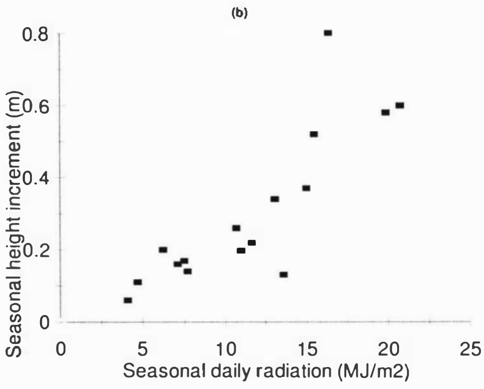
8.3 Results

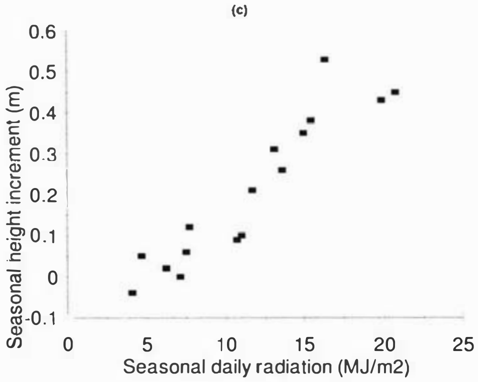
8.3.1 Height

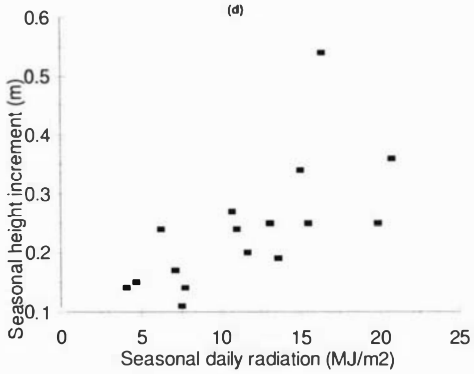
The scatterplots of seasonal radiation against seasonal height increment for each species show that, for most species, the relationship was strong and linear (Figure 8.1). The R^2 for the regression between radiation and height increment (Table 8.2) ranged from 0.45 (*E. cladocalyx*) to 0.87 (*E. botryoides*). There were significant slope differences among species ($P = 0.05$) for the regression of seasonal radiation on seasonal height increment. The slopes for individual species generally reflected performance (mean height) at age 5 years. For example, the slopes for *E. nitens* (0.050), *E. regnans* (0.047) and *E. obliqua* (0.046) were significantly ($P = 0.05$) higher than those of *E. cladocalyx* (0.014) and *E. microcorys* (0.021), remaining species being intermediate.

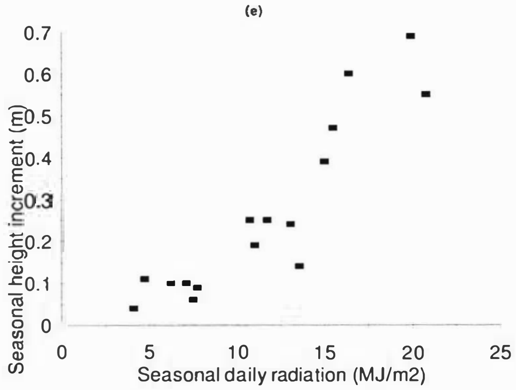
Rainfall did not influence seasonal height increment in any species but the effect of windrun was significant in seven species ($P \leq 0.05$); *E. agglomerata*, *E. baxteri*, *E. cladocalyx*, *E. microcorys*, *E. muelleriana*, *E. nitens* and *E. pilularis*. After the inclusion of windrun in the regression equations the R^2 for these species increased (0.77, 0.83, 0.61, 0.86, 0.76, 0.74 and 0.84 for *E. agglomerata*, *E. baxteri*, *E. cladocalyx*, *E. microcorys*, *E. muelleriana*, *E. nitens* and *E. pilularis* respectively.

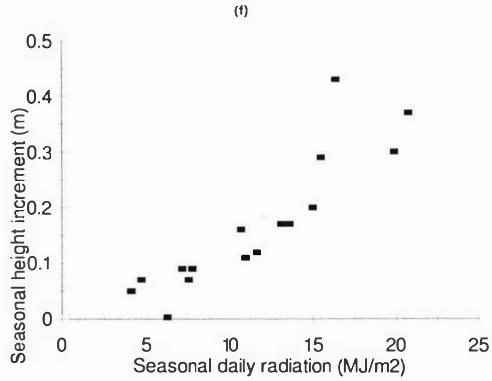

(g)
Seasonal height increment (m)
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(b)
Seasonal height increment (m)
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(c)
Seasonal height increment (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(d)
Seasonal height increment (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(e)
Seasonal height increment (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(f)
Seasonal height increment (m)
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)

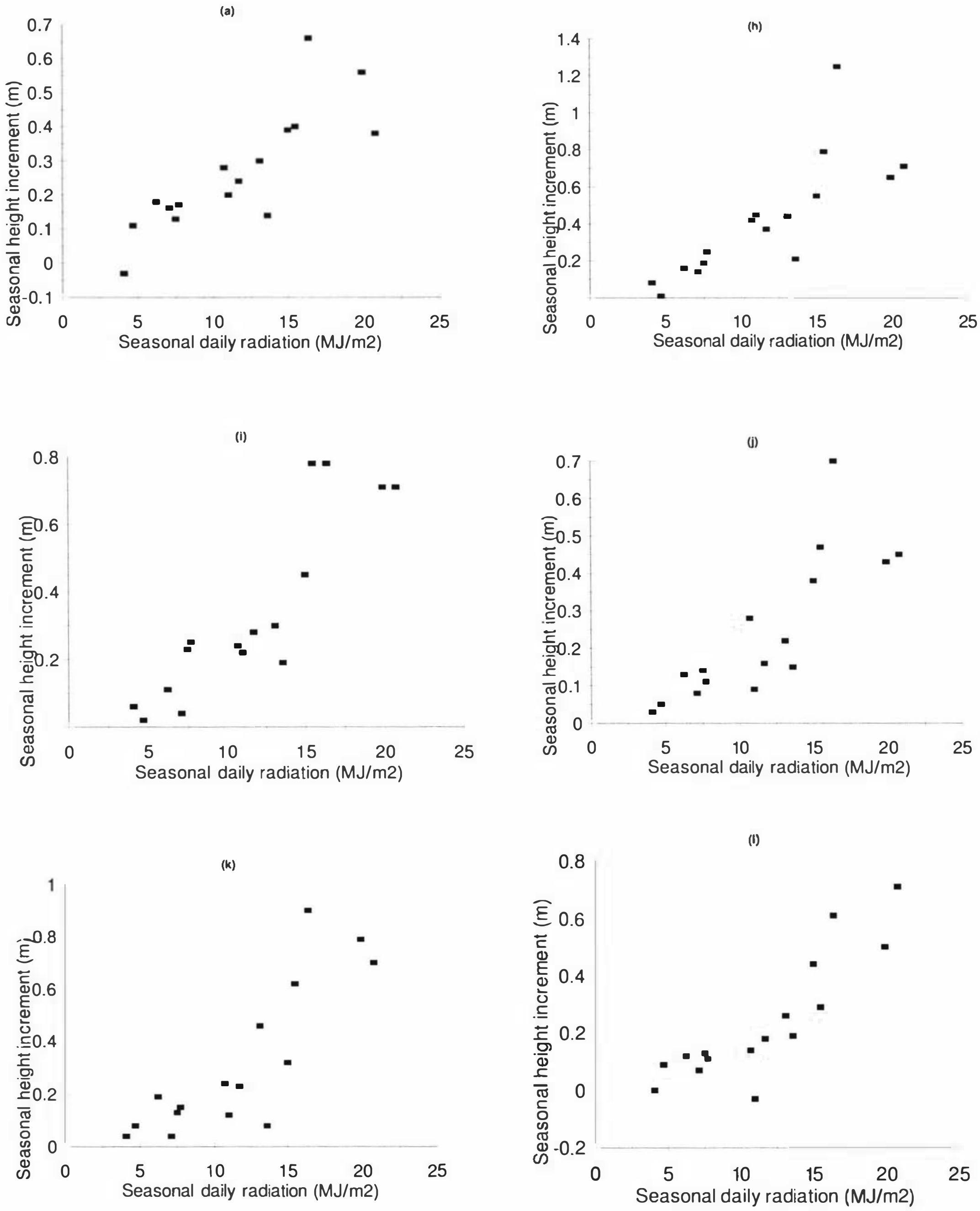


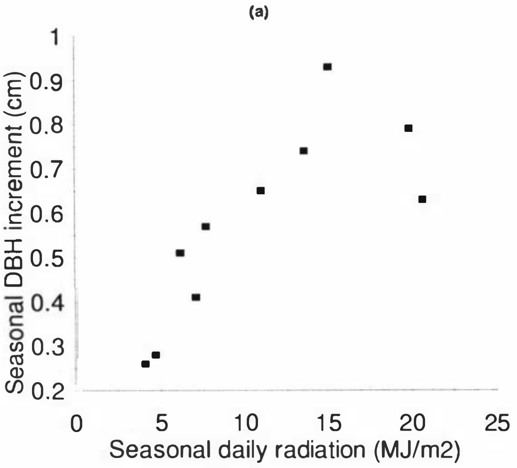
Figure 8.1 Scatterplots of seasonal mean daily solar radiation (MJ/m^2) against mean seasonal height increment (m) for (a) *E. agglomerata*, (b) *E. baxteri*, (c) *E. botryoides*, (d) *E. cladocalyx*, (e) *E. globoidea*, (f) *E. microcorys*, (g) *E. muelleriana*, (h) *E. nitens*, (i) *E. obliqua*, (j) *E. pilularis*, (k) *E. regnans* and (l) *E. saligna* from June 1997 to August 1999.

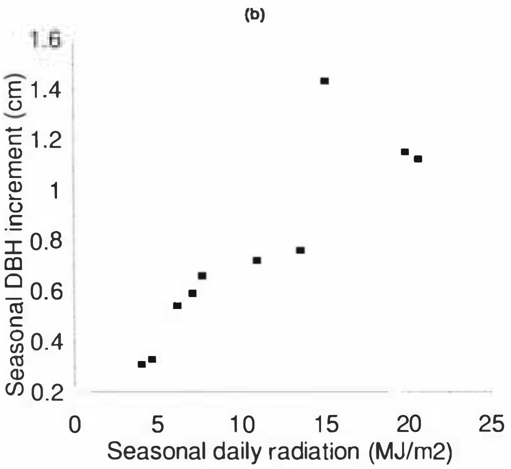
Table 8.2 The slope and coefficient of determination for the regression of seasonal mean daily radiation (MJ/m^2) against seasonal height increment (m) for each species. Numbers in parentheses = SEM.

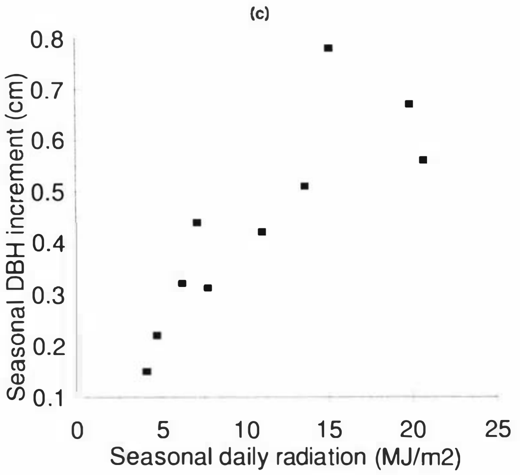
	Radiation	R^2
E. agglomerata	0.029 (0.005)	0.69
E. baxteri	0.035 (0.006)	0.70
E. botryoides	0.033 (0.003)	0.87
E. cladocalyx	0.014 (0.004)	0.45
E. globoidea	0.037 (0.005)	0.83
E. microcorys	0.021 (0.003)	0.80
E. muelleriana	0.031 (0.007)	0.61
E. nitens	0.050 (0.010)	0.64
E. obliqua	0.046 (0.007)	0.78
E. pilularis	0.030 (0.006)	0.67
E. regnans	0.047 (0.008)	0.70
E. saligna	0.037 (0.006)	0.75

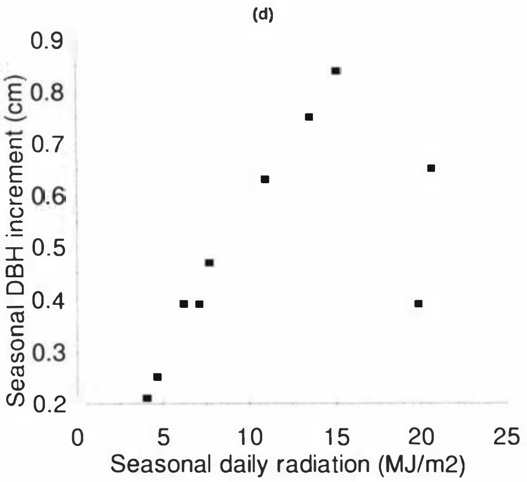
8.3.2 DBH

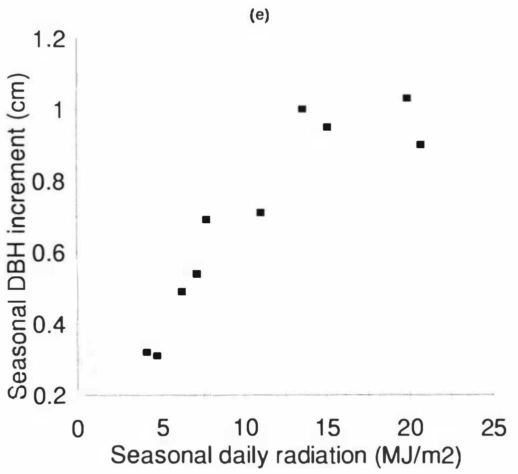
The scatterplots of seasonal diameter increment against seasonal radiation are shown in Figure 8.2. The relationship appeared to be curvilinear for most species, diameter growth levelling off at higher radiation levels. There was considerable species variation in the relationship between diameter growth and radiation (Table 8.3), species rankings being similar to those for height. However, species slope differences in Table 8.3 were mostly not significant ($P = 0.05$), the exception being that between *E. baxteri* (0.50) and *E. cladocalyx* (0.20). The relationship between diameter growth and radiation was strongest in *E. globoidea* ($R^2 = 0.81$) but was relatively weak for *E. cladocalyx*, *E. microcorys*, *E. pilularis* and *E. saligna* ($R^2 = 0.38$, 0.44, 0.40 and 0.42 respectively) and marginally significant for *E. cladocalyx* ($P = 0.057$). Including seasonal rainfall in the regression resulted in an improvement in the R^2 in most species, but was only significant ($P \leq 0.05$) for *E. botryoides*, *E. microcorys* and *E. saligna.* Windrun had no effect on diameter increment in any species.

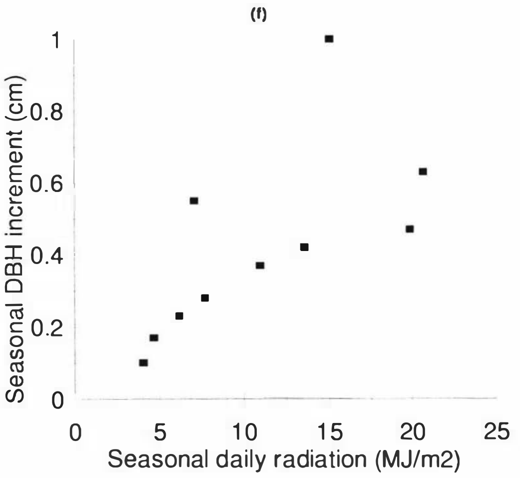

(a)
Seasonal DBH increment (cm)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(b)
Seasonal DBH increment (cm)
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(c)
Seasonal DBH increment (cm)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(d)
Seasonal DBH increment (cm)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(e)
Seasonal DBH increment (cm)
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)


(f)
Seasonal DBH increment (cm)
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
Seasonal daily radiation (MJ/m2)

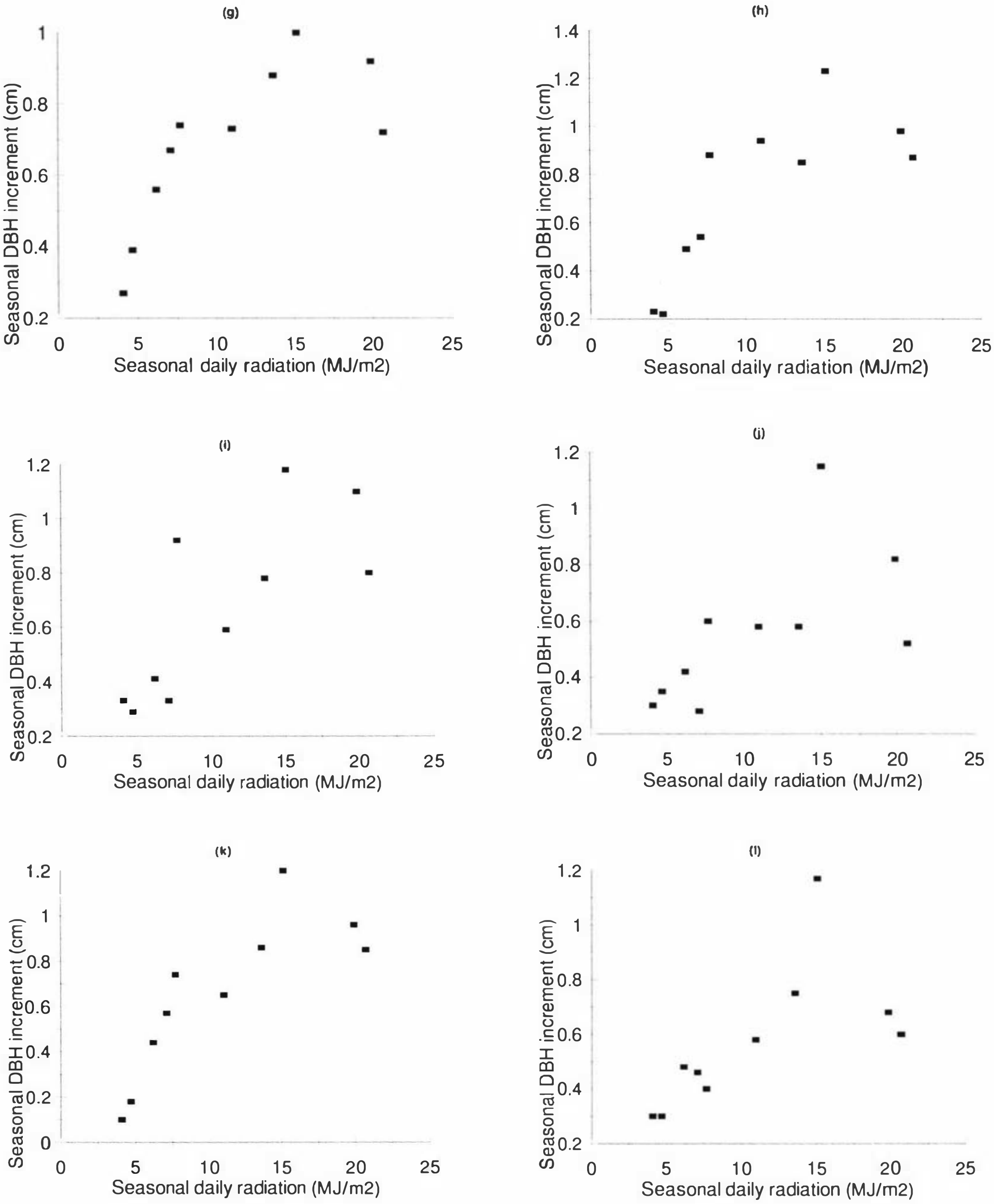


Figure 8.2 Scatterplots of seasonal mean daily solar radiation (MJ/m^2) against the seasonal DBH increment (cm) for (a) *E. agglomerata*, (b) *E. baxteri*, (c) *E. botryoides*, (d) *E. cladocalyx*, (e) *E. globoidea*, (f) *E. microcorys*, (g) *E. muelleriana*, (h) *E. nitens*, (i) *E. obliqua*, (j) *E. pilularis*, (k) *E. regnans and* (l) *E. saligna* from June 1998 to August 1999.

Table 8.3 Slope and coefficient of determination (R^2) for the regression of seasonal mean daily radiation (MJ/m^2) against seasonal DBH increment (cm) for each species from June 1998 to August 1999 and the coefficient of determination ($*R^2$) after inclusion of seasonal rainfall. Numbers in parentheses = SEM.

	Radiation	R^2	$*R^2$
E. agglomerata	0.03 (0.008)	0.61	0.70
E. baxteri	0.05 (0.010)	0.77	0.81
E. botryoides	0.03 (0.006)	0.72	0.86
E. cladocalyx	0.02 (0.010)	0.38	0.63
E. globoidea	0.04 (0.007)	0.81	0.85
E. microcorys	0.03 (0.011)	0.44	0.70
E. muelleriana	0.03 (0.009)	0.56	0.69
E. nitens	0.04 (0.013)	0.58	0.61
E. obliqua	0.04 (0.012)	0.59	0.60
E. pilularis	0.03 (0.012)	0.40	0.49
E. regnans	0.05 (0.012)	0.65	0.75
E. saligna	0.03 (0.011)	0.42	0.73

8.4 Discussion

Figures 8.1 and 8.2 show that the seasonal and aspect variation in growth at Tuapaka has been largely driven by variation in solar radiation. Tree growth is linearly related to the amount of solar radiation intercepted by the canopy (Whitehead and Beadle 2004), which is determined by the canopy leaf area and leaf area duration (Taiz & Zeiger 1998). The curvilinear relationship between solar radiation and DBH increment is probably a reflection of the greater sensitivity of diameter growth to moisture stress, limiting diameter growth during summer when radiation levels are highest (Honeysett et al 1992). The significant effect of seasonal rainfall on diameter growth in some species supports this but the small diameter growth data set probably limited the ability of the analysis to detect significant effects in some species (Steel &

Torrie 1980). Cambium activity is sensitive to moisture stress, resulting in reduced diameter growth, primarily of latewood (MacFarlane and Adams 1998). Dry conditions may result in increased allocation of assimilates to tree roots, including eucalypts (Beets & Whitehead 1996; Moroni et al 2003), also reducing diameter growth of the stem (Beets & Whitehead 1996). Dehydration during dry weather can result in stem shrinkage (Hingston & Galbraith 1998).

Species differences in growth at Tuapaka may be due to species differences in radiation interception and the efficiency of conversion of radiation to biomass, both of which are influenced by environmental factors such as temperature and moisture stress. For example, species able to maintain a high leaf area (Honeysett et al 1992) and/or maintain a high leaf water potential during dry conditions will intercept more radiation, have a higher radiation conversion efficiency, and therefore greater productivity, than species less adapted to moisture stress (White et al 1999).

Information on solar radiation in New Zealand is limited, a result of the small number of meteorological stations recording solar radiation (21), though radiation can be estimated from sunshine hours (97 stations) for most regions (NZ Meteorological Service 1983). Furthermore, regional estimates of radiation do not take account of local topographic effects, such as aspect and slope angle in hill country. However, it is possible to approximate radiation on a micro scale using information on solar geometry, local topography and solar radiation measurements from a proximate horizontal surface (McAneney & Noble 1976). Consideration of the direct and diffuse components of solar radiation, which are strongly influenced by cloud cover, has resulted in improved prediction of global solar radiation in New Zealand hill country (R^2 for predicted versus actual radiation > 0.95) (Tian et al 2001).

8.5 Summary

Tree growth on different aspects and seasons at Tuapaka was strongly influenced by solar radiation. The relationship between height growth and solar radiation was linear while that between diameter growth and radiation curvilinear; diameter growth probably being limited by moisture stress at high radiation levels. Consideration of the influence of topography on solar radiation, in conjunction with other environmental factors, may allow potential forest production to be more reliably assessed on a micro scale in hill country.

Chapter 9

Final Discussion and Conclusions

9.1 Introduction

The final discussion will consider the broad issues associated with this study, primarily the interpretation of the results for tree growers interested in establishing eucalypts for saw log production in the southern North Island. Interpretation will include consideration of the applicability of results for slope aspects other than north and south, the risks associated with planting site sensitive species and the limitations imposed by the restricted period over which performance was measured. Conclusions from the study will also be presented here.

9.2 Microsite

Mean stem volume on the shady face was only 54.0% of that on the sunny, raising questions about the viability of planting eucalypts on southerly aspects. In other regions where the buffering effects of wind and cloud cover are less important aspect differences in productivity may be even greater due to greater temperature differences (Radcliffe & Lefever 1981). Other aspects (easterly, westerly) will be represented on many hill country sites and although the performance of eucalypts was not assessed on other aspects, it may be possible to estimate relative performance based on expected radiation and temperature regimes on these microsites. Solar radiation and temperature differences between northerly and southerly aspects represent extremes (Holland & Steyn 1975). Radiation on easterly and westerly aspects in middle latitude regions can be expected to be intermediate to these extremes (Kumar & Skidmore 2000), resulting in intermediate temperatures (Lambert & Roberts 1975) which, in the absence of other limiting factors, indicates that growth on other aspects would also be intermediate (Paton 1980). Environmental factors other than solar radiation and temperature which may vary with aspect include evapotranspiration, wind and soil fertility (Lambert & Roberts 1976; Lambert 1977). The distribution of different aspects in hill country is variable. On the flanks of the Tararua Range for example, aspects are predominantly westerly or easterly. However, many New Zealand hill country farms contain a mix of different aspects (Saggar et al 1999). Aspect differences in radiation are also influenced by slope angle, differences increasing with increasing slope angle, the maximum difference coinciding with about 30° slope angle in the middle latitudes (Holland & Steyn 1975).

Aspect differences in productivity at Tuapaka may increase as trees age. There was certainly divergence in aspect growth over the assessment period. Aspect differences may initially increase because the light compensation point in eucalypts increase with age (Ashton & Turner 1979). This would result in trees on the shady face being disadvantaged compared to those on the sunny; low radiation restricting achievement of the light compensation point, reducing net photosynthesis. However, as biomass accumulation proceeds on the sunny face, resulting in increased evapotranspiration, trees are more likely to suffer from soil moisture limitation to growth than those on the shady, particularly in dry summers. Trees on the shady face may eventually attain sufficient height to receive direct sunlight at all times of the year, particularly trees on the upper slope (Jacobs 1955; Florence 1996). While this suggests that trees on the upper shady face may eventually be less constrained by low solar radiation, they will nevertheless continue to be constrained by the influence of exposure (Bulloch 1991).

9.3 Species

All species were disadvantaged by conditions on the shady face, consistent with the general categorisation of eucalypts as intolerant species (Florence 1996). The species evaluated at Tuapaka are diverse, representing different subgenera and groups, suggesting that the slower growth experienced on the shady face would not be atypical for potentially useful species. While species differences at Tuapaka need to be treated with caution because of the potential influence of provenance on performance (Wilcox 1982; Wilcox et al 1985), several species were represented by provenances which have performed well in New Zealand. These include *E. botryoides* (Barr 1996), *E. nitens* (Miller et al 1992) and *E. pilularis* (Barr 1996). Seed was sourced from either the Australian Tree Seed Centre, CSIRO or Proseed New Zealand. The Proseed catalogue stated that their policy was to supply seed from provenances with proven performance (Proseed 1994) while the Australian Tree Seed Centre policy was, in the absence of specific knowledge of provenances, to select provenances which are climatically adapted to local conditions and therefore more likely to perform well (Craig Gardiner, Australian Tree Seed Centre, CSIRO, personal communication). However, it is not possible to be completely certain of the performance of all provenances used in this study.

Australian research has found that the early growth of *Monocalyptus* species is typically slower than that of *Symphyomyrtus* species (Turnbull et al 1993) an advantage that begins at establishment and partially results from larger seed, quicker germination and initial growth (Davidson & Reid 1980). However, over time *Monocalyptus* species catch up (Cotterill et al 1985). Mean DBH and height of different subgenera (Table 8.1) at different ages suggests that the growth pattern at Tuapaka was consistent with these observations. Orthogonal contrasts of the mean height ($P < 0.003$) and DBH ($P < 0.0001$) of *Monocalyptus* and *Symphyomyrtus* species at Tuapaka at age 5 reveals that *Monocalyptus* species have actually performed better than *Symphyomyrtus* species. Mean DBH of *Monocalyptus* and *Symphyomyrtus* species at Tuapaka was 9.3 cm and 7.6 cm respectively, and mean height was 5.6 m and 5.3 m respectively. However there was considerable variation among *Symphyomyrtus* species (CV = 44.7% and 32.4% for DBH and height respectively) including the best (*E. nitens*) and the poorest (*E. microcorys* and *E. cladocalyx*) species, whereas variation (CV = 31.5% and 22.6% for DBH and height respectively) in performance of *Monocalyptus* species was lower.

Table 9.1 Mean height (m) and DBH (cm) of *Monocalyptus* and *Symphyomyrtus* species at different ages (years).

		DBH		Height	
		Monocalyptus	Symphyomyrtus	Monocalyptus	Symphyomyrtus
Age	2	-	-	1.7	1.8
	3	3.9	4.0	2.9	2.8
	4	5.9	5.3	4.0	3.8
	5	9.2	7.6	5.6	5.3

New Zealand research has also shown that over time *Monocalyptus* species have recovered from a relatively slow start. For example, Hathaway and King (1986) ranked 15 eucalypt species at Pakaraka and Kahuiti in the Wairarapa based on height growth. At Kahuiti, which was a less favourable site than Pakaraka, the best four species and 10 of the top 15 species, based on height at age 5 years, were *Symphyomyrtus*. However, by age 12 years three of the top four species were *Monocalyptus* (Bulloch 1991). In contrast, the best species at Pakaraka at age 5 years were *Monocalyptus*, perhaps highlighting the ecological advantages *Symphyomyrtus* species have under challenging conditions (Noble 1989).

The performance of each species up to age 5 years is summarised in Table 8.2. *E. nitens* was clearly superior in terms of growth and form but produced wood of low density. The best of the remaining species in terms of growth, *E obliqua* and *E. regnans* also produced low density wood. Conversely, those species with the highest wood density, *E. cladocalyx* and *E. microcorys*, had poor growth. The pest problems associated with *E. botryoides* and *E. saligna* at Tuapaka, and the recent arrival of other pests which severely damage these species in New Zealand support the recommendation that these species no longer be planted in New Zealand (Hay 1995).

Among the stringybark species, *E. muelleriana* performed well, reinforcing previous assessments that it is probably the best stringybark species in New Zealand, at least for sites free of hard frosts (Barr 1996; Shelbourne et 2002; Hocking 2003b; Shelbourne et 2003). However, the performance of *E. baxteri* was promising, particularly diameter growth (Table 7.7). Wood from mature *E. baxteri* trees is similar to that of *E. muelleriana* and its natural range extends to much higher elevations than that of *E. muelleriana* (Boland et al 1984), suggesting that it may be a potentially useful alternative in southern and high altitude sites where frost may damage *E. muelleriana.*

Table 9.2 Summary of the performance of individual species at Tuapaka. ++ = clearly superior; + = good; 0 = intermediate; - = poor and - - = clearly inferior.

	DBH	Height	Form	Wood density	Health
E. agglomerata	0	0	0	0	+
E. baxteri	0	0	0	0	+
E. botryoides	-	0	- -	0	- -
E. cladocalyx	-	0	0	++	+
E. globoidea	0	0	0	0	+
E. microcorys	- -	- -	0	+	+
E. muelleriana	0	0	0	0	+
E. nitens	++	++	++	-	0
E. obliqua	0	+	0	-	0
E. pilularis	0	0	0	0	+
E. regnans	0	+	0	-	0
E. saligna	0	0	0	0	- -

9.4 Relevance of assessments of young trees

Trees at Tuapaka were 5 years old at the time of assessment for growth, form and basic density, whereas clearfell ages for most eucalypts managed for sawlogs in New Zealand are typically 35 years or more (Nicholas 1991; Barr 1996). Consequently, the value of information from relatively young stands needs to be considered. For example, the accuracy of prediction of trees suitable for selection of final crop in stands of *Pinus radiata* improves with age (Maclaren 1995). The following discussion will briefly examine the relevance of assessments of young trees for predicting future performance, including growth, form and wood density.

9.4.1 Growth

While the results of assessments undertaken at early ages must be treated with caution, New Zealand studies have shown that growth performances at different ages at the same site may be strongly correlated, indicating that the results from assessments of young trees may be useful indicators of later performance. For example, Shelboume et al (2003) compared the species mean height and DBH of 12 and 22 year old eucalypts (10 year age interval) at Kahuiti in the Wairarapa. The correlation between DBH age 12 and DBH age 22 was 0.75 and highly significant. Maclaren (1995) found that the correlation between DBH at age 32 years and earlier assessments in *P. radiata* increased, approaching 1.0, as the age interval decreased; a correlation of 0.75 being achieved at an age interval of 17 years. In this study the correlations between species mean DBH at ages 3 and 5 years and species mean height at ages 2 and 5 years were both 0.87 ($P = 0.0002$). Shelbourne et al (2000b) found that the correlation between family mean DBH at age 2 and 6 years in *E. muelleriana* was only 0.55. Reference to the individual tree correlations within species at Tuapaka revealed that the DBH and height age interval correlations in *E. muelleriana* were similar to those of other species. However, the Shelbourne et al (2000b) study also found that families differed in crown health score at age 6 and that crown health score was correlated with DBH increment (2-6 years). Differential influences from pests and diseases (Wilcox et al 1985) and thinning operations (Maclaren 1995) may influence age interval growth correlations.

9.4.2 Form

Correlations between assessments of form at different ages can be poor in eucalypts (Shelbourne et al 2000b; Shelbourne et al 2003). This may be because in young eucalypts early assessment of form may encounter trees without a clearly defined central leader but which later forms when trees enter the pole stage (Jacobs 1955). Trees may also be able to correct stem defects such as lean, kink and wobble by both straightening of the pith and by differential diameter growth (Maclaren 1995). While assessment of form at young ages may not provide a particularly reliable guide to form in older trees, the need to select potential crop trees, when initial decisions concerning pruning and thinning are being made (Forest Research Institute 1987), means that form assessments at early ages are meaningful.

9.4.3 Wood density

The strong genetic control over wood density (Haslett 1988b; 1990) means that generally species differences in wood density are quite consistent across a wide range of ages (McKinley et al 2000). Wood density assessments of individual species at different ages are also strongly correlated (Miranda et al 2001; Osorio et al 2003). Variation due to site is generally much less than that due to species (Low & Shelbourne 1999; McKinley et al 2000). Consequently, species basic wood density differences at age 5 can reliably indicate relative species differences in older trees and on other sites.

9.5 Implications for tree growers

The influence of aspect on performance in this study, particularly growth, was substantial. Tree growers on hill country sites need to take this into account if they want to maximise the potential economic benefits from producing eucalypt sawlogs. Should eucalypts be blanket planted on hill country? Aspect differences in diameter growth suggests that clearfell ages on different aspects will also differ. The high costs of roads and machinery needed for logging in hill country (Vos & Clarke 1995) and the reduction in the scale of operation means that this would be a considerable disincentive. Stratification of hill country, based on aspect, may facilitate differential management which may help overcome aspect differences in tree growth.

Diameter growth in eucalypts is responsive to stocking rate (Opie et al 1978; McKenzie & Hay 1996), suggesting that a possible strategy to overcome differential growth would be to carry different final crop stocking rates on different aspects; reducing stocking rates on shady aspects will increase diameter growth, potentially resulting in trees on both aspects achieving minimum DBH for clearfell at about the same age. An alternative would be to increase the stocking rate on the sunny face but this would result in greater age to achieve minimum DBH for clearfell.

The computerised stand management decision support system, PC-Standpak (Forest Research Institute 1993), was utilised to model the influence of different final crop stocking rates at Tuapaka. While primarily focussed on *P. radiata* it also includes growth models for other species including *E. nitens*. This is an empirical model developed from permanent sample plot data from Tasmania, Australia and New Zealand (Candy 1997). To model the growth of *E. nitens* on the shady and sunny faces the Stand Growth module of Standpak was utilised. Initially the appropriate growth and height models were selected in the "Models" screen. Subsequently the mean DBH, mean crop height, initial stocking (800 stems/ha) as well as planting date and the starting date for the growth simulation for each aspect was entered into the "Initial stand" screen in turn. This allowed estimation of site index. Management was limited to thinning down to different final crop stocking rates in the "Treatments" screen. Each aspect was modelled at 100 and 150 stems/ha final crop. Thinning was undertaken at 10 years. Growth simulations for each aspect with different final crop stocking rates were produced in the "Grow" screen. Limitations in the *E. nitens* growth model meant that final crop stocking could not be reduced below 100 stems/ha and stand age could not exceed 33 years.

The simulations predict that at 33 years DBH on the sunny face will be 7.2 and 5.8 cm greater than that on the shady face at 100 and 150 stems/ha, respectively (Table 8.3). While these simulations are limited by age an indication of the extent of the reduction in stocking rate required on the shady face to achieve similar DBH to that on the sunny face at clearfell can be seen by comparing the DBH on the shady face at 100 stems/ha (47.1 cm) with that on the sunny face at 150 stems/ha (48.2 cm).

Table 9.3 Mean aspect DBH (cm) of *E. nitens* at 100 and 150 stems/ha final crop stocking predicted by Standpak growth simulation to 33 years.

	Stocking	
	100	150
Shady	47.1	42.4
Sunny	54.3	48.2

Another strategy to minimise the disadvantages of differential aspect growth is to grow alternative species other than *Eucalyptus* on the shady face. Species likely to have similar rotation length and with good economic potential include the cypresses, *Cupressus lusitanica* and *C. macrocarpa* and hybrids of these (Maclaren 2005; Nicholas 2005). In addition, shady sites, such as southerly aspects, may actually be an advantage when growing cypresses (Hocking 2003b) because cooler temperatures on shady sites help reduce the severity of cypress canker, a fungal disease caused by

Seridium cardinale and *S. unicorne*, and, cypresses are generally tolerant of shady conditions (Hocking 2006). Choice of species will depend on exposure; *C. lusitanica* is less tolerant of exposed conditions than *C. macrocarpa* (Hay 1995). The wood of these species is similar (Clifton 1990).

9.6 Conclusions

Climate

Microsite influenced temperature, solar radiation and exposure. The sunny face experienced higher radiation receipts and higher maximum and mean temperatures than the shady. Differences were greatest during the winter months and least during the summer but were generally modest; the difference in aspect monthly mean daily temperature was always less than 1.0°C. This was probably because of the buffering effect of the, typically, cloudy and windy conditions at the trial site. Few air frosts were recorded; minimum air temperatures rarely fell below 0°C on either aspect. Higher elevation microsites were more exposed than those at lower elevation.

Seedling mortality

Seedling mortality to the end of the first summer post planting was generally low, losses being less than 10% in most species, the exception being *E. cladocalyx* (15%) which suffered greater losses than all other species. Microsite affected mortality; the sunny face experienced higher losses than the shady, but slope position had no influence. Possum browse damage was a problem after planting but, apart from one species (*E. microcorys*), was confined to the sunny face. Possum browsing did not influence survival to the end of the first summer.

Foliar nutrients

Microsite had a small influence on foliar nutrient concentrations. However, concentrations of N and K were lower, but Ca and Mg concentrations higher, on the lower shady microsite.

There were large species differences in foliar nutrient concentrations. *Symphyomyrtus* species generally had higher concentrations of N, P, K and Ca, but lower Mg, than *Monocalyptus*. However, there were group differences within subgenera; within *Symphyomyrtus* the eastern blue gums had higher nutrient concentrations than other species while in *Monocalyptus* the stringybark species had lower nutrient concentrations than the ash species. There were also subgeneric differences in nutrient correlations. In particular, no N-P correlations were found in *Monocalyptus* species whereas strong N-P correlations were found in most *Symphyomyrtus* species. This suggests that there may be intrinsic subgeneric differences in ability to take up key macronutrients.

Comparison of nutrient concentrations achieved at Tuapaka in species for which published 'normals' are available indicated that N may have been sub-optimal but that remaining nutrients were adequate. DBH and height at age 5 were positively associated with N, P and K concentrations, particularly in *Symphyomyrtus* species.

Foliar N concentration was positively correlated with DBH at age 5 years in 3 species, all *Symphyomyrtus* but the correlation was only strong in *E. nitens*. However, N was not correlated with height in any species. There were strong negative correlations between Ca and Mg concentrations and DBH and height in *E. cladocalyx* and *E. microcorys*. Otherwise correlations between foliar nutrient concentrations and growth were atypical.

Seasonal growth

Height and diameter growth were strongly seasonal in all species. Diameter growth peaked during the spring while height growth peaked during in the summer in most species. Seasonal growth was better on the sunny face in most species but the magnitude of the difference varied with season; during the summer growth on the shady face was similar to or better than that on the sunny face whereas in the winter growth on the sunny face was much higher than on the shady, reflecting aspect seasonal solar radiation and temperature differences. Height and diameter growth on different aspects and in different seasons was largely driven by the amount of incoming daily solar radiation.

Height, DBH and stem volume at age 5

There was a large aspect effect on both DBH and height. Growth on the sunny face was significantly higher than that on the shady in all species. The net effect of this was that at age 5 mean individual stem volume on the shady face was 54% that of the sunny. Slope position had no effect on height growth but DBH was reduced on the lower slope; this resulted in mean stem volume on the lower slope being significantly less than on the upper slope.

There was also a large species effect on both DBH and height. *E. nitens* had better growth than all other species. The second best group included the ashes, *E. regnans* and *E. obliqua.* This was followed by a large group including all of the stringybarks, while the poorest species were *E. microcorys* and *E. cladocalyx.*

Analysis of covariance of the effect of possum browsing of seedlings following planting revealed that at age 5 years there was still some residual influence; browsed seedlings having lower DBH, height and stem volume than non browsed. However, means adjustment for possum browsing did not alter the assessed performance of individual species.

Basic wood density

Basic wood density at age 5 was strongly influenced by species whereas microsite had no influence. Species rankings for density generally reflected the wood density characteristics of mature trees, though densities achieved were less than the densities reported from mature trees. Density was highest in *E. cladocalyx* (594 kg/m^3) and lowest in *E. nitens* (426 kg/m^3) and the ash species (438 and 413 kg/m^3 in *E. obliqua* and *E. regnans* respectively). The stringybark species generally produced wood of intermediate density, the exception being *E. baxteri* which was similar to the lighter species. Basic density was not correlated with DBH in most species.

Basic wood density of individual species at Tuapaka was moderately correlated with mean basic density of the same species from two sites in the Wairarapa region.

Stem form

Stem form was influenced by both microsite and species. The best form was found in *E. nitens* and the poorest in *E. botryoides*; poor form in this species may have been due to canopy damage resulting from possum browsing. Trees on the upper shady microsites had poorer form than those on other microsites, probably as a result of wind damage, being the most exposed microsite.

Pests and diseases

Pests had a significant impact on the performance of *E. botryoides* and *E. saligna.* During the winter months both species suffered extensively from possum browsing but possum browsing incidence was highest in *E. botryoides.* The *Eucalyptus* gall wasp, *Ophelimus eucalypti*, was also widespread on both species; many individual trees of both species being heavily attacked. Both pests were more likely to be found on larger trees, probably because these trees had higher foliar N concentrations and therefore more palatable to the pests. Several fungal diseases were recorded, but incidence and attributed losses were minor.

Lateral root distribution

Analysis of lateral root distribution revealed that lateral roots were generally well distributed; strong laterals were typically present in all quadrants, facilitating good stability. Comparison of the number and distribution of the lateral roots of two species on each aspect revealed no species or microsite differences. There was some evidence that aspect influenced the distribution of biomass in the lateral roots. Trees on the shady face allocated proportionately more assimilates to a smaller number of laterals than those on the sunny.

Relationship between environmental factors and stem volume and stem form

High foliar N, P and K concentrations were negatively associated with stem form in *Symphyomyrtus* species whereas in *Monocalyptus* foliar nutrients appeared to have little influence on stem volume or form. However, form was negatively associated with exposure and stem volume was negatively associated with slope angle in *Monocalyptus* species.

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Appendices

Appendix 1 Daily mean, maximum and minimum temperatures (°C) June 1996 to May 1997 for the shady and sunny aspects and the gully bottom.

	Shade			**Sun**			**Gully**		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
June	7.9	11.4	4.6	8.4	12.1	4.7	7.9	11.7	4.0
July	8.3	11.0	5.6	8.7	11.9	5.6	8.1	11.3	5.0
August	8.4	11.0	4.8	8.8	12.7	4.9	8.3	12.5	4.2
Sept	11.7	15.4	8.0	12.0	15.9	8.1	11.8	15.9	7.7
Oct	12.0	16.1	7.9	12.2	16.5	8.0	12.0	16.5	7.5
Nov	12.0	15.9	8.2	12.3	16.4	8.1	12.0	16.2	7.9
Dec	15.0	19.8	10.2	15.0	19.9	10.1	14.7	19.6	9.7
Jan	15.7	21	10.4	15.9	21.5	10.4	15.4	20.6	10.1
Feb	17.8	22.8	12.9	18.3	23.6	13.0	17.5	22.5	12.5
Mar	15.4	19.3	11.7	16.1	20.6	11.7	15.5	19.4	11.5
April	12.2	16.5	8.0	13.0	18.1	7.8	12.2	16.9	7.5
May	12.8	16.4	9.3	13.6	18.0	9.1	12.5	16.3	8.6

Appendix 2 Daily mean, maximum and minimum temperatures (ºC) June 1997 to May 1998 for the shady and sunny aspects.

	Shade			**Sun**		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**
June	8.5	11.9	5.0	9.2	13.4	4.9
July	7.8	11.4	4.2	8.6	13.2	4.0
August	8.6	12.0	5.2	9.3	13.3	5.2
Sept	9.5	13.1	5.9	10.2	14.4	6.0
Oct	11.4	15.1	7.8	11.9	16.0	7.8
Nov	13.2	17.4	9.1	13.5	18.0	8.9
Dec	15.1	20.1	10.1	15.1	20.3	10.0
Jan	16.7	21.7	11.8	16.8	22.2	11.5
Feb	19.5	24.3	14.7	20.1	25.5	14.8
Mar	17.9	22.7	13.1	18.6	24.3	13.0
April	14.9	19.5	10.3	15.4	20.7	10.2
May	11.0	14.7	7.3	11.7	16.3	7.2

Appendix 3 Daily mean, maximum and minimum temperatures (ºC) June 1998 to May 1999 for the shady aspect.

	Shade		
	Mean	**Max**	**Min**
June	9.5	13.0	6.1
July	10.7	13.7	7.6
August	8.7	12.2	5.2
Sept	11.3	15.3	7.3
Oct	12.6	15.9	9.3
Nov	13.4	18.2	8.8
Dec	15.9	20.3	11.5
Jan	19.3	24.7	13.8
Feb	18.7	24.7	12.7
Mar	18.9	23.7	14.1
April	14.4	18.7	10.1
May	12.4	15.9	8.9

Appendix 4 Long term daily mean, maximum and minimum temperatures (°C) and rainfall (mm) at AgResearch (1928 to 1997, NZ station EO5363).

	Temperature			**Rainfall**
	Max	**Min**	**Mean**	
June	12.6	4.9	8.8	96.4
July	11.9	4.2	8.1	90.2
August	13.1	5.1	9.1	92.7
Sept	14.7	6.7	10.7	76.2
Oct	16.5	8.4	12.5	87.0
Nov	18.5	10.0	14.2	78.0
Dec	20.6	11.7	16.0	86.1
Jan	22.0	12.9	17.4	76.5
Feb	22.3	13.0	17.6	50.7
Mar	20.9	11.7	16.3	71.6
April	18.1	9.5	13.8	77.3
May	15.0	7.0	11.0	86.2

Appendix 5 Mean daily maximum, minimum and average temperatures (°C), daily sunshine (hours), rainfall (mm) and daily wind run (km) recorded at AgResearch, Palmerston North for the June 1996 to May 1997, June 1997 to May 1998 and June 1998 to May 1999 periods.

1996/97

	Temperature					
	Max	**Min**	**Mean**	**Sun**	**Rainfall**	**Windrun**
June	12.4	4.6	8.5	3.4	98.5	145.6
July	12.2	5.8	9.0	3.1	104.8	119.6
August	13.2	4.2	6.7	4.1	82.3	162.7
Sept	16.5	7.0	11.7	4.5	102.8	165.7
Oct	17.0	9.1	13.1	5.4	95.6	206.9
Nov	17.1	9.3	13.2	5.6	100.5	286.4
Dec	20.3	11.4	15.8	6.6	91.1	217.1
Jan	21.0	11.8	16.4	7.8	68.0	217.2
Feb	22.8	13.6	18.2	5.7	58.0	189.9
Mar	19.9	12.4	16.2	4.4	68.1	183.4
April	17.3	7.5	12.4	4.7	144.7	158.6
May	17.2	8.7	12.9	4.5	24.3	129.0
Mean	**17.2**	**8.8**	**13.0**	**5.0**	**86.6**	**181.8**

1997/98

	Temperature					
	Max	**Min**	**Mean**	**Sunshine**	**Rainfall**	**Windrun**
June	13.1	3.9	8.5	3.7	60.4	99.6
July	12.7	3.0	7.9	4.7	32.0	100.3
August	13.1	5.4	9.2	4.5	60.1	152.6
Sept	14.2	6.7	10.5	3.9	79.0	168.7
Oct	16.2	8.4	12.3	4.3	77.8	205.1
Nov	18.1	10.8	14.4	6.4	57.1	314.2
Dec	20.4	11.2	15.8	6.8	103.4	212.6
Jan	22.0	13.1	17.5	5.8	31.7	197.1
Feb	25.1	15.5	20.3	6.4	61.4	164.4
Mar	23.1	13.3	18.2	6.0	35.6	170.7
April	19.9	10.7	15.3	5.3	72.9	149.8
May	15.9	7.4	11.6	3.8	100.9	111.4
Mean	**17.8**	**9.1**	**13.4**	**5.1**	**64.4**	**170.5**

1998/99

	Temperature					
	Max	**Min**	**Mean**	**Sunshine**	**Rainfall**	**Windrun**
June	14.0	6.2	10.1	2.3	143.5	114.2
July	14.7	7.2	10.9	3.0	162.5	104.6
August	13.2	5.9	9.5	3.5	57.9	132.1
Sept	16.3	7.5	11.9	4.9	72.7	169.3
Oct	17.4	10.5	14.0	4.9	194.4	261.4
Nov	18.9	9.9	14.4	7.1	93.9	265.9
Dec	20.8	12.3	16.6	6.7	36.4	340.8
Jan	25.0	14.9	19.9	8.2	39.4	283.1
Feb	24.9	13.1	18.9	9.0	20.1	258.7
Mar	23.9	14.3	19.1	6.3	34.3	223.0
April	19.3	10.1	14.7	5.9	65.3	249.6
May	16.9	7.6	12.2	3.3	114.6	171.5
Mean	18.8	9.9	14.3	5.4	86.3	214.7

Appendix 6 The Wilcoxon signed-rank test for the influence of slope position on the % of browsed seedlings for each species on the sunny face.

This test allows comparison of two groups of matching data (pairs) provided that data is at least ordinal, allowing differences between pairs to be ranked. The procedure involves listing matched pairs and calculating the difference between individual pairs. In this case the matched pairs are based on species so there are 12 pairs. Initially the difference sign is ignored. If there is no difference between a pair of observations then that pair is not ranked. Differences are then ranked according to their absolute value, lowest differences ranking first, and the ranks signed according to the signs of the differences between the pairs. When absolute differences between pairs are the same, an average rank is assigned. This is demonstrated in the worked example below. The differences of three pairs are given a rank of 3, the average of 2, 3 and 4. The positive and negative ranks are then summed. If there is no difference between the pairs (null hypothesis), the sums of the signed ranks should be the same. The lowest absolute value of the sum of the positive or negative ranks is compared with critical values.

The difference in possum browse incidence (%) between slope positions on the sunny face and the signed rank of the difference for each species.

	Sunny Top	Sunny Bottom	Difference	Signed Rank
E. agglomerata	61.4	4.3	57.1	8
E. baxteri	67.1	4.3	62.8	10
E. botryoides	71.4	10	61.4	9
E. cladocalyx	14.3	0	14.3	3
E. globoidea	18.6	14.3	4.3	1
E. microcorys	90	4.3	85.7	11
E. muelleriana	38.6	14.3	24.3	6
E. nitens	38.6	57.1	-18.5	-5
E. obliqua	10	10	0	
E. pilularis	18.6	32.9	-14.3	-3
E. regnans	4.3	18.6	-14.3	-3
E. saligna	75.7	32.9	42.8	7

Sum of the positive ranks = 55

Sum of the negative ranks = 11

The lowest absolute value is used as the test statistic. A table of critical values for comparisons including from 6 to 25 pairs is provided in Steel and Torrie, (1980). Test values lower than the critical values are significant. In this case the test value is 11, the same as the critical value (P = 0.05) for 11 pairs, meaning that it is just significant at the 5.0% level of probability. Consequently, the null hypothesis that there is no difference in possum browse damage between the upper and lower slopes on the sunny aspect is rejected.

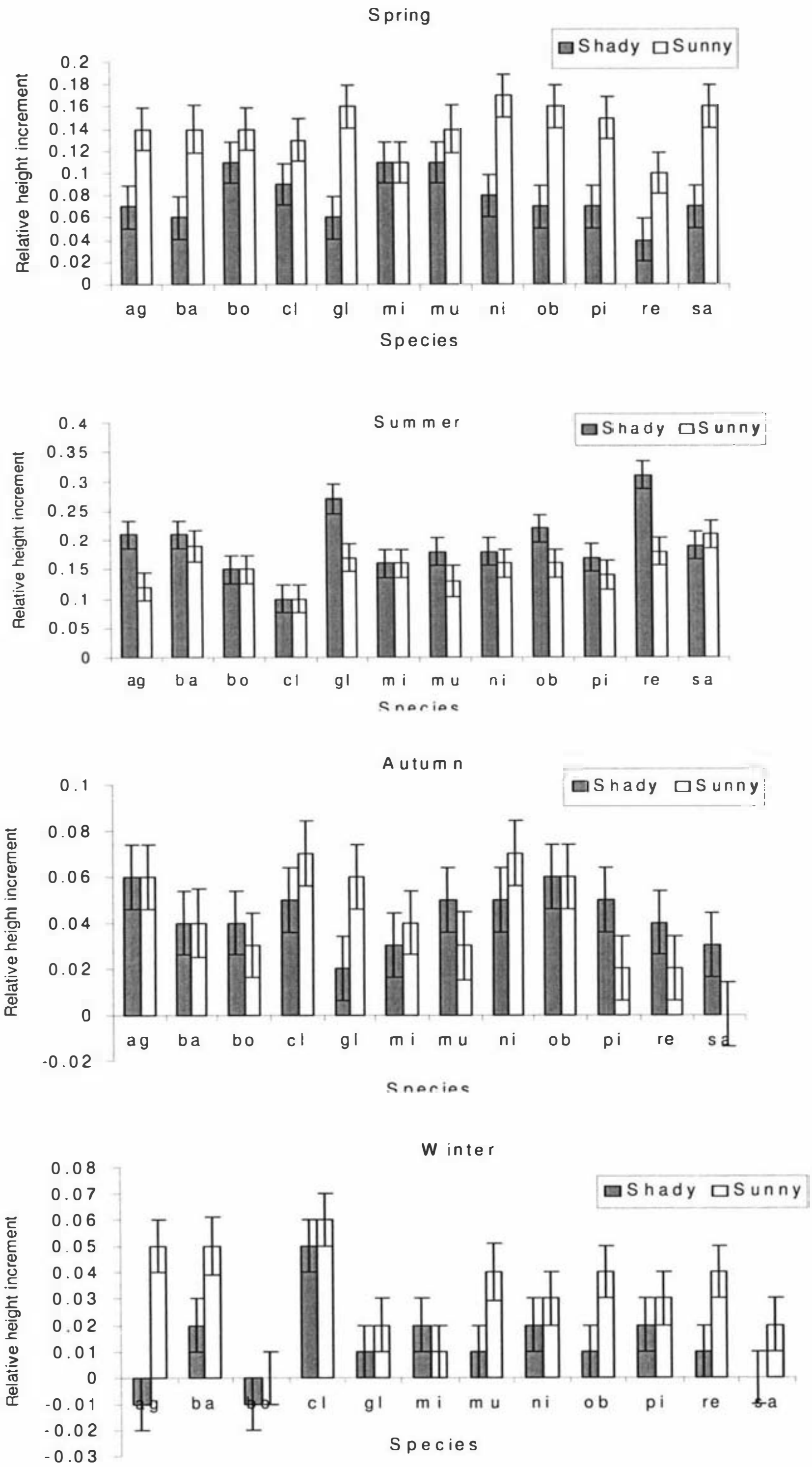
Appendix 7 Foliar nutrient concentrations and principal components scores (first three components) by species and subgenus.

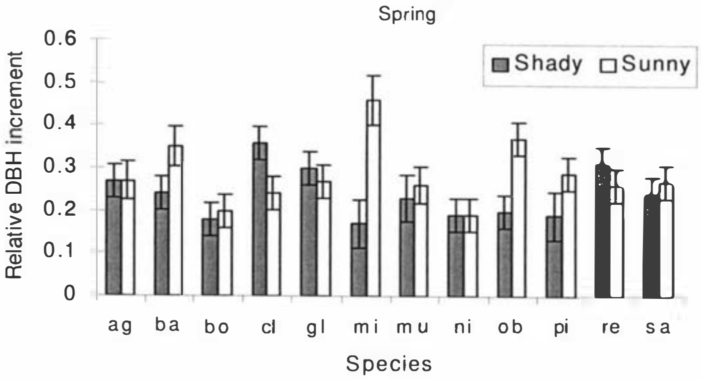
Obs	trt	subgen	N	P	K	Ca	Mg	Prin1	Prin2	Prin3
1	1	1	8.4	1.60	4.50	7.01	3.65	-2.00451	1.59745	0.27700
2	1	1	9.9	1.34	4.70	6.63	3.63	-2.04359	1.05949	0.28846
3	1	1	10.1	1.34	4.89	5.66	3.42	-1.94644	0.48923	-0.06362
4	1	1	10.2	1.16	6.63	4.42	2.36	-1.43364	-1.41158	0.33450
5	1	1	10.3	1.38	5.69	6.53	3.21	-1.48754	0.55919	0.54817
6	1	1	11.2	1.39	5.43	5.95	3.16	-1.40418	0.35364	0.17946
7	1	1	11.2	1.64	4.78	4.80	2.98	-1.27414	0.20398	-0.63757
8	1	1	12.1	1.81	6.86	5.80	2.97	-0.11054	0.50020	-0.06661
9	1	1	12.8	1.50	8.83	4.51	3.13	0.10874	-0.52549	-0.25097
10	1	1	12.9	1.22	5.43	5.37	2.74	-1.25398	-0.46755	0.18198
11	1	1	13.2	1.20	6.32	4.84	2.56	-0.91942	-0.97583	0.14621
12	1	1	14.5	1.31	8.07	4.33	2.84	-0.02838	-1.00357	-0.21074
13	2	1	10.6	1.33	4.20	5.26	2.66	-1.93035	-0.25946	0.03891
14	2	1	10.9	1.28	10.87	4.49	1.37	0.51017	-2.71281	1.36301
15	2	1	11.0	1.46	4.85	3.85	2.51	-1.49294	-0.82316	-0.64394
16	2	1	11.7	1.54	5.93	3.82	2.48	-0.88054	-0.90322	-0.61450
17	2	1	12.0	1.27	6.69	4.26	2.50	-0.94687	-1.19966	-0.04604
18	2	1	12.0	1.47	5.18	4.73	2.52	-1.12908	-0.52460	-0.24092
19	2	1	12.8	1.41	6.50	3.07	1.78	-0.54367	-2.06582	-0.45853
20	2	1	12.8	1.55	5.71	4.07	2.23	-0.65065	-0.99199	-0.46579
21	2	1	12.8	1.82	6.34	3.51	2.66	-0.18481	-0.52797	-1.16586
22	2	1	12.9	1.66	8.39	4.59	2.41	0.39454	-0.86652	-0.03991
23	2	1	13.2	1.59	5.13	6.75	3.24	-0.79719	1.03541	0.15504
24	2	1	13.8	1.25	7.25	3.77	2.31	-0.42491	-1.65417	-0.20424
25	3	2	12.1	1.11	8.33	6.71	3.10	-0.62931	-0.21245	1.22896
26	3	2	13.2	1.84	5.84	8.17	3.16	-0.10069	1.72258	0.75755
27	3	2	14.8	1.28	6.36	4.93	3.38	-0.67105	-0.09656	-0.44871
28	3	2	15.6	2.66	6.76	8.53	3.12	1.89265	2.81025	0.10580
29	3	2	16.7	1.94	8.38	6.93	2.51	1.64422	0.46580	0.53210
30	3	2	16.8	1.97	9.32	8.72	3.10	1.97457	1.56095	1.19241
31	3	2	19.1	1.91	11.84	5.01	2.62	3.06730	-0.66055	-0.11983
32	3	2	19.6	1.98	9.48	4.95	2.72	2.46464	-0.16381	-0.64818
33	3	2	20.0	1.97	10.72	6.79	3.34	2.88890	0.88024	0.08345
34	3	2	20.3	2.08	9.90	6.12	2.87	2.91375	0.47690	-0.23632
35	3	2	22.4	2.24	10.52	7.58	2.80	3.85674	1.08002	0.31732
36	3	2	22.8	2.16	9.59	6.78	2.89	3.44600	0.89158	-0.21128
37	4	2	10.2	1.29	5.57	11.13	3.10	-1.39305	2.03242	2.98090
38	4	2	11.4	1.24	5.98	9.02	2.77	-1.13776	0.83968	2.14277
39	4	2	13.9	1.22	7.50	5.91	2.43	-0.27597	-0.84078	0.85409
40	4	2	14.2	1.57	9.51	8.13	1.93	1.19692	-0.28733	2.15548
41	4	2	14.5	1.50	7.48	7.88	1.88	0.48490	-0.23322	1.81778
42	4	2	14.6	1.83	7.03	10.32	2.29	0.87641	1.54153	2.40118
43	4	2	14.7	1.35	8.70	7.93	2.30	0.60718	-0.21162	1.92074
44	4	2	14.8	1.48	6.54	6.21	2.33	0.00371	-0.33066	0.59978
45	4	2	17.2	1.32	10.40	6.11	1.93	1.59304	-1.48741	1.32727
46	4	2	18.8	1.59	9.10	5.14	2.32	1.72262	-0.93564	0.06102
47	4	2	19.8	1.75	10.40	6.59	2.45	2.62673	-0.25244	0.66938
48	4	2	21.9	1.92	9.17	5.51	2.22	2.87315	-0.44682	-0.22847
49	5	1	8.4	1.13	4.13	5.54	3.72	-2.91073	0.53490	-0.07482
50	5	1	10.3	1.18	7.74	4.64	3.25	-1.22223	-0.65586	0.07973
51	5	1	10.4	1.39	4.45	4.44	3.48	-2.04255	0.22875	-0.83837
52	5	1	12.0	1.37	5.63	4.28	2.64	-1.18134	-0.78019	-0.36692
53	5	1	12.5	1.11	5.67	4.09	3.11	-1.57396	-0.78469	-0.49029
54	5	1	12.8	1.11	6.67	4.08	2.84	-1.12334	-1.17271	-0.22113

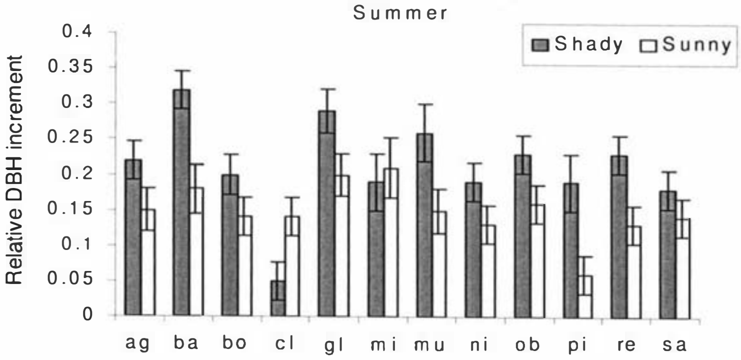
55	5	1	12.9	2.15	4.70	5.01	3.70	-0.38782	1.64053	-1.57319
56	5	1	13.3	1.31	7.21	3.83	2.57	-0.50661	-1.31040	-0.35205
57	5	1	13.7	1.20	6.13	3.49	2.79	-1.01574	-1.23332	-0.71545
58	5	1	14.8	1.41	5.42	4.49	3.01	-0.72572	-0.28176	-0.72696
59	5	1	15.4	1.37	6.30	4.70	2.61	-0.27104	-0.74432	-0.27275
60	5	1	15.9	1.59	6.03	4.37	2.85	-0.01790	-0.30904	-0.86461
61	6	2	9.7	1.02	7.07	5.65	2.56	-1.56948	-1.03557	1.07298
62	6	2	11.1	1.26	6.10	6.22	2.25	-1.15966	-0.64198	1.05556
63	6	2	11.4	1.39	6.42	4.77	2.21	-0.87859	-1.07454	0.25071
64	6	2	11.6	1.07	7.07	4.89	2.03	-1.04327	-1.72138	0.81263
65	6	2	11.8	1.13	7.10	5.64	2.40	-0.95389	-1.03543	0.91022
66	6	2	14.1	1.31	8.82	4.12	1.86	0.36368	-2.07181	0.36622
67	6	2	14.6	1.06	7.63	3.77	1.76	-0.29004	-2.46302	0.29476
68	6	2	14.8	1.34	9.41	3.78	1.93	0.70096	-2.17390	0.16536
69	6	2	14.9	1.17	7.84	4.84	2.13	-0.03130	-1.61727	0.52061
70	6	2	15.2	1.42	7.58	4.51	2.09	0.29731	-1.39571	0.06975
71	6	2	15.5	1.20	7.09	4.59	2.26	-0.16248	-1.44382	0.14547
72	6	2	17.0	1.53	8.53	3.98	1.90	1.13461	-1.74228	-0.18312
73	7	1	10.9	1.57	5.51	7.75	4.01	-1.27673	2.01267	0.45215
74	7	1	11.3	1.82	4.58	5.73	3.98	-1.24580	1.72094	-0.94899
75	7	1	12.2	1.32	5.17	5.01	3.27	-1.47674	0.05225	-0.38416
76	7	1	12.8	1.68	8.11	5.78	3.55	0.10542	0.66450	-0.13717
77	7	1	13.1	1.98	5.71	6.50	3.60	-0.15793	1.72000	-0.47267
78	7	1	13.3	1.33	6.31	4.00	2.16	-0.66476	-1.46489	-0.18777
79	7	1	13.3	1.70	5.37	5.22	3.34	-0.64847	0.68389	-0.74578
80	7	1	14.4	1.29	6.28	4.22	3.16	-0.74733	-0.53003	-0.67428
81	7	1	14.4	1.34	6.34	4.43	3.48	-0.71978	-0.10443	-0.78998
82	7	1	14.4	1.78	6.53	4.88	3.01	0.12245	0.20882	-0.71861
83	7	1	14.5	1.82	9.10	4.85	2.91	1.06582	-0.19949	-0.35579
84	7	1	15.7	1.49	6.45	5.92	3.15	-0.04982	0.33188	-0.08576
85	8	2	11.3	1.25	4.47	6.26	2.38	-1.69927	-0.29391	0.76560
86	8	2	11.8	1.28	4.71	6.74	3.04	-1.61132	0.48542	0.60701
87	8	2	12.5	1.12	6.59	5.34	2.26	-0.98322	-1.21246	0.72887
88	8	2	12.9	1.25	4.11	7.09	2.73	-1.54444	0.37782	0.82471
89	8	2	14.7	1.47	8.04	5.32	1.83	0.53206	-1.33216	0.66764
90	8	2	14.8	1.36	8.25	3.93	1.85	0.37713	-2.00090	0.09814
91	8	2	15.3	1.43	9.24	4.91	1.93	0.93687	-1.61419	0.57981
92	8	2	15.9	1.61	6.58	8.83	2.38	0.55488	0.84373	1.67821
93	8	2	16.3	1.46	8.92	3.56	1.61	1.07074	-2.30886	-0.05714
94	8	2	16.7	1.53	6.54	6.21	2.33	0.44528	-0.26019	0.42212
95	8	2	16.9	1.35	9.06	3.66	1.39	1.13110	-2.64029	0.20596
96	8	2	17.3	1.43	9.17	3.29	1.49	1.31671	-2.59078	-0.12564
97	9	1	12.2	1.39	4.40	6.68	3.56	-1.60324	1.12765	0.10490
98	9	1	12.7	1.76	4.91	5.46	3.68	-0.89650	1.22464	-0.90217
99	9	1	13.3	1.68	5.76	6.23	3.31	-0.48579	0.94318	-0.14984
100	9	1	13.6	2.72	4.82	8.29	4.43	0.62747	4.25902	-0.94975
101	9	1	13.8	1.84	4.61	6.00	3.76	-0.65374	1.64669	-0.87509
102	9	1	14.3	1.51	4.71	6.51	3.51	-0.91658	1.14304	-0.16883
103	9	1	14.4	1.56	6.03	4.79	3.11	-0.39156	0.03647	-0.66981
104	9	1	16.0	1.84	8.17	4.50	2.76	1.09725	-0.30281	-0.70055
105	9	1	16.9	1.91	5.27	5.68	4.07	0.17399	1.81634	-1.39105
106	9	1	17.0	1.53	7.12	4.52	3.16	0.39964	-0.20817	-0.81992
107	9	1	18.5	1.77	7.70	4.24	2.91	1.27537	-0.28859	-1.07848
108	9	1	18.8	1.46	7.04	3.81	2.55	0.72719	-1.10065	-0.89482
109	10	1	10.0	1.55	3.95	9.10	5.72	-2.32732	4.24178	0.02653
110	10	1	10.8	1.20	4.66	5.99	4.54	-2.34075	1.46388	-0.46367
111	10	1	11.5	1.45	4.59	6.26	4.36	-1.80489	1.75162	-0.53705
112	10	1	11.6	1.07	7.05	4.89	2.03	-1.04984	-1.71856	0.80976
113	10	1	12.1	1.11	5.30	4.86	4.19	-1.98914	0.52386	-0.73595
114	10	1	12.5	1.03	5.62	4.41	3.42	-1.76354	-0.48992	-0.43069
115	10	1	13.3	1.27	8.15	3.52	3.01	-0.37957	-1.21281	-0.57696
116	10	1	13.3	1.75	6.29	4.48	3.40	-0.32959	0.40681	-1.06611
117	10	1	14.2	1.42	6.54	5.74	3.58	-0.52678	0.54479	-0.23160
118	10	1	15.3	1.38	5.64	6.34	3.93	-0.71741	1.15341	-0.29083

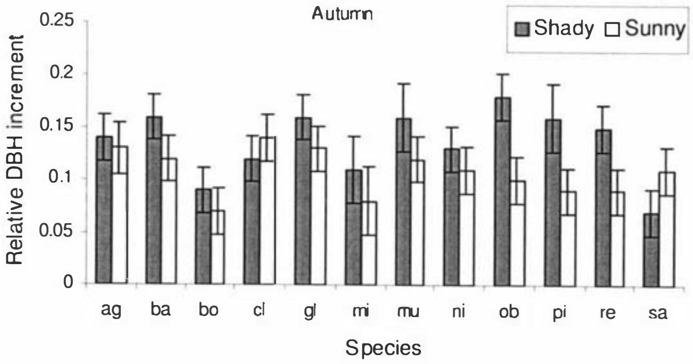
119	10	1	15.5	1.62	4.71	6.58	3.61	-0.54340	1.41049	-0.38085
120	10	1	16.3	1.24	6.14	4.27	3.51	-0.57880	-0.24180	-0.94197
121	11	1	9.9	1.34	4.70	6.63	3.63	-2.04359	1.05949	0.28846
122	11	1	14.9	1.76	5.10	5.06	3.16	-0.30487	0.58461	-0.93134
123	11	1	15.3	1.51	6.40	4.63	2.76	-0.09339	-0.45745	-0.51108
124	11	1	15.9	1.76	5.05	5.19	3.47	-0.19440	0.92040	-1.11387
125	11	1	16.2	1.82	5.85	5.44	3.54	0.21104	1.04454	-0.99404
126	11	1	16.9	1.57	6.16	4.92	2.93	0.20126	-0.08045	-0.66358
127	11	1	17.4	1.44	6.46	4.77	2.80	0.22990	-0.47172	-0.52547
128	11	1	17.7	1.72	7.44	4.49	2.47	1.08161	-0.62755	-0.64172
129	11	1	17.8	1.53	7.41	4.97	2.70	0.78574	-0.49950	-0.35098
130	11	1	17.8	1.71	7.54	4.80	2.51	1.12703	-0.50588	-0.49193
131	11	1	18.5	1.66	7.61	3.79	2.61	1.13220	-0.86136	-1.03746
132	11	1	20.5	1.24	6.98	4.30	2.12	0.84722	-1.60020	-0.31206
133	12	2	14.9	1.49	7.78	7.61	3.90	0.14610	1.43822	0.58189
134	12	2	15.1	1.50	7.79	6.65	3.69	0.19933	0.91060	0.19890
135	12	2	15.9	1.81	6.02	11.54	4.02	0.42104	3.66645	1.83108
136	12	2	17.0	1.55	8.63	7.55	2.93	1.14955	0.50451	1.01439
137	12	2	17.2	1.97	9.10	7.56	3.97	1.70597	1.95524	0.07051
138	12	2	17.4	1.78	8.01	8.94	3.79	1.23065	2.19053	0.87959
139	12	2	18.5	1.72	7.99	7.37	3.62	1.30273	1.38619	0.17616
140	12	2	20.7	2.07	9.78	7.08	3.51	2.83757	1.40928	-0.14940
141	12	2	21.6	2.14	8.96	7.76	3.23	2.95062	1.61642	0.09721
142	12	2	22.7	1.97	9.95	6.12	3.45	3.09608	0.84668	-0.60324
143	12	2	23.6	2.24	11.34	5.59	3.24	4.14130	0.63741	-0.88233
144	12	2	25.9	2.24	10.78	6.01	2.84	4.52343	0.51075	-0.68440

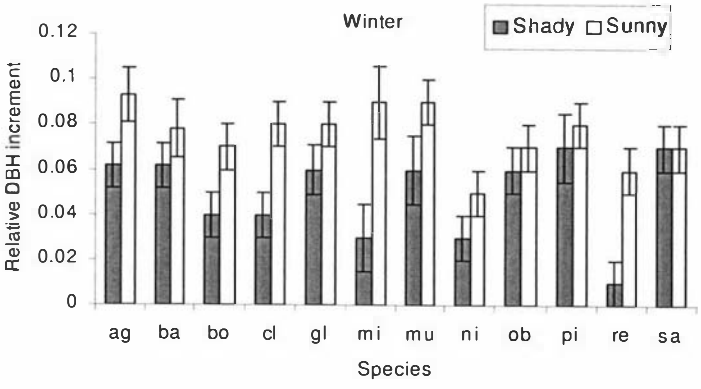
Appendix 8 Effect of species and aspect on relative seasonal height and diameter growth. Error bars = 2 x SEM.




Spring
Relative DBH increment
0.6
0.5
0.4
0.3
0.2
0.1
0
Shady
Sunny
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species


Summer
Relative DBH increment
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Shady
Sunny
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa


Autumn
Relative DBH increment
0.25
0.2
0.15
0.1
0.05
0
Shady
Sunny
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species


Winter
Relative DBH increment
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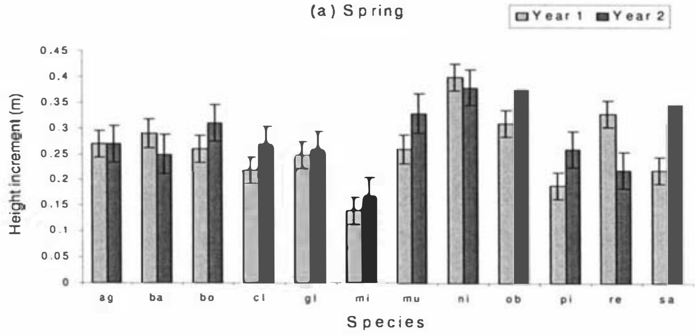
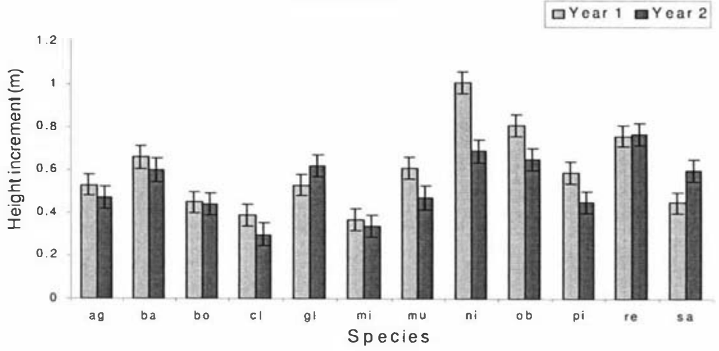
0.1
0.08
0.06
0.04
0.02
0
Shady
Sunny
ag
ba
bo
cl
gl
mi
mu
ni
ob
pi
re
sa
Species

Appendix 9 The interaction between species, year and season on height growth (m) during (a) spring, (b) summer, (c) autumn and (d) winter in year 1 (September 1997 to August 1998) and year 2 (September 1998 to August 1999). Error bars = 2 x SEM.

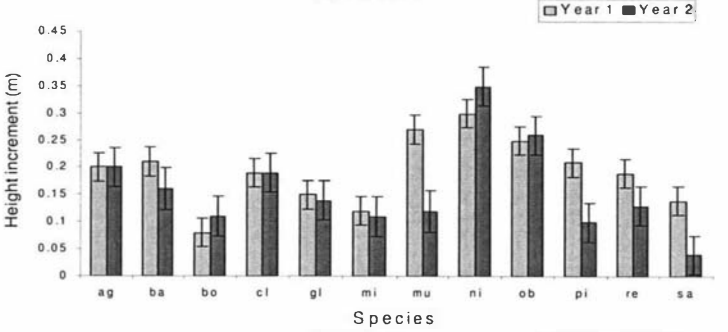
(a) Spring



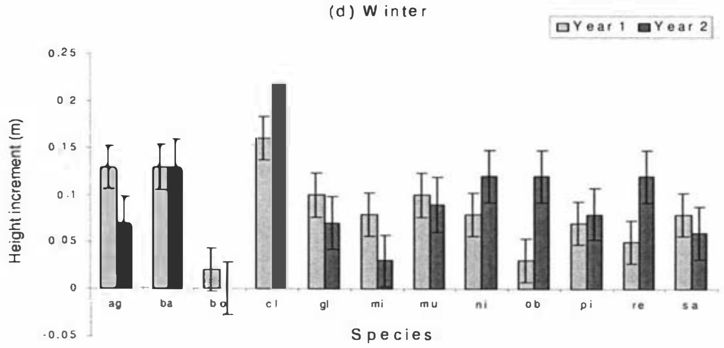
(b) Summer



(c) Autumn



(d) Winter



Appendix 10 Smalian's formula and formula for the volume of a cone

Log section volume (dm^3) $= 0.03927 \times (SED^2 + LED^2) \times L$

Where:		
	SED	= under bark small end diameter (cm)
	LED	= under bark large end diameter (cm)
	L	= log length (m)
	0.03927	$= \pi/80$

Cone volume $= (L \times \pi \times radius^2) / 3$

Appendix 11 The Petterson function

Tree height $= 1.4 + (\beta + \alpha/DBH)^{-2.5}$

To allow calculation of the coefficients, α and β, the linear form may be utilised.

$DBH/(height - 1.4)^{0.4} = \alpha + \beta(DBH)$