



An Australian Government Initiative



Impact of Insects on Eucalypt Plantations in the Murray Valley

**A report for the
RIRDC/L&WA/FWPRDC/MDBC
Joint Venture Agroforestry Program**

by Rob Floyd and Grant Farrell

June 2007

RIRDC Publication No 07/085
RIRDC Project No CSE-72A

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ISBN 1 74151 482 7
ISSN 1440-6845

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Published in June 2007

Foreword

Major tree establishment programs are being pursued in the Murray-Darling Basin and elsewhere, aimed at eucalypt plantations for landcare and commercial wood production. One of the regions being developed is the Murray Valley around Shepparton and Deniliquin. Many young plantations in the Murray Valley have incurred heavy defoliation from a range of insects and the two most commonly planted species, *Eucalyptus grandis* and *E. globulus*, are quite susceptible to insect feeding.

Prior to this study, the impact of insect damage on the rate of production of eucalypt plantations in the Murray Valley had not been quantified, even though severe defoliation by insects has occurred. This report provides some assessments of productivity losses due to insect damage, and presents comparative data on the relative susceptibility of various species of eucalypts as well as within-species differences in insect resistance. The report also evaluates the economic impact of insect damage on eucalypt plantations in the Murray Valley, through modelling of management scenarios.

The report also discusses the current and continuing needs for the development of non-chemical insect management options, not only to reduce production losses, but also to maintain the “freedom to operate” for this emerging industry based on multi-purpose plantations in agricultural landscapes.

The report will assist plantation managers, farm foresters and researchers to understand, manage and minimise insect damage in young eucalypt plantations.

This project was funded by the Joint Venture Agroforestry Program (JVAP), which is supported by three R&D Corporations—Rural Industries Research and Development Corporation (RIRDC), Land & Water Australia, and Forest and Wood Products Research and Development Corporation (FWPRDC), together with the Murray-Darling Basin Commission (MDBC). The R&D Corporations are funded principally by the Australian Government. State and Australian Governments contribute funds to the MDBC.

This report, a new addition to RIRDC’s diverse range of over 1600 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems. The JVAP, under this program, is managed by RIRDC.

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Peter O’Brien

Managing Director

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Acknowledgments

A number of organisations collaborated with CSIRO Entomology to provide the trial sites needed for this project. Thanks go to Goulburn Valley Water for the Daldy Road Farm site near Shepparton and to Lower Murray Water for the site at the Koorlong Wastewater Treatment and Re-use Centre near Mildura. In particular, we wish to acknowledge the help and assistance of George Wall and Peter Ebner managers, respectively, of the Daldy Road Farm and Koorlong Wastewater Treatment and Reuse Centre. Roger Arnold of CSIRO Forestry and Forest Products coordinated that Division's running of the Deniliquin sites and we thank him for his help and collaboration as well as for technical advice and assistance. We also would like to thank the Deniliquin landholders, Ken Crossley, Donald Barclay and Jim Hermiston, for granting access to their properties. The Lyneham Ridge site near Canberra was kindly provided by ACT Forests. Thanks also go to the following CSIRO Entomology staff: Mamoru Matsuki who gave advice on data analysis on the chapters he was not involved in writing, Martin Steinbauer for discussions on autumn gum moth ecology and John Dowse, Rex Sutherland, Michelle Michie and Wendy Whitby for technical assistance during the project. We thank Harry Recher for review of the draft report, and Rosemary Lott for technical edits on the final report.

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Executive Summary

What the report is about

This report provides some assessments of productivity losses in eucalypt plantations in the Murray Valley due to insect damage. It presents comparative data on the relative susceptibility of various species of eucalypts, as well as within-species differences in insect resistance. The report also presents an economic evaluation of various management scenarios for insect pest management, and addresses the need for the development of non-chemical insect management options, not only to reduce production losses, but also to maintain the “freedom to operate” for this emerging industry based on multi-purpose plantations in agricultural landscapes.

Who is the report targeted at?

The report will assist plantation managers, farm foresters and researchers to understand, manage and minimise insect damage in eucalypt plantations. It is also for researchers who seek optimal management of other types of plantation research trials.

Background

Major tree establishment programs aimed at eucalypt plantations for landcare and commercial wood production are being pursued in the Murray Darling Basin and elsewhere. One of the regions being developed is the Murray Valley around Shepparton and Deniliquin. Some 100,000 ha of plantations are proposed for the area. Many young plantations in the Murray Valley have incurred heavy defoliation from a range of insects including leafblister sawfly (*Phylacteophaga* spp.), autumn gum moth (*Mnesampela privata*), and a number of psyllid species (*Cardiaspina* spp.). The two most commonly planted species of eucalypts, *Eucalyptus grandis* and *E. globulus*, are quite susceptible to insect feeding and have, in extreme outbreaks, incurred high levels of mortality. A number of the older plantations have also been damaged by borers (*Phoracantha* spp.).

Previously, the impact of insect damage on the rate of production of eucalypt plantations in the Murray Valley had not been quantified, even though severe defoliation by insects has occurred in a number of plantations (Neumann and Collett 1992). The role of resistance in plantation pest management has been reviewed by Floyd and Farrow (1994), and preliminary observations on relative resistance of provenances of *E. camaldulensis* and *E. globulus* in the Murray Valley have been reported (Farrow *et al.* 1994; Floyd *et al.* 1994).

Aims/Objectives

The project’s aims were to:

1. Assess provenances and families of several species of eucalypts for resistance to pests of young trees, in order to incorporate resistance into breeding programs in seed orchards.
2. Measure the impact of insect feeding on the growth and form of young eucalypts grown in existing and new plantations established under irrigation or high water table sites in the Murray Valley, and to incorporate this information into growth and damage models.
3. Develop a set of recommendations for the environmentally sensitive management of insect pests involving insect resistance in young trees for use in farm forestry.
4. Evaluate the economic cost of insect damage within plantations in the Murray Valley through modelling management scenarios.

Methods used

The project used a combination of seed orchards and purpose planted trials at sites across the Murray Valley and collected data on tree growth, insect damage and the phenology of insect pests. Levels of insect damage were assessed for several species (*Eucalyptus globulus*, *E. grandis*, *E. benthamii*

(including *E. dorrigoensis* and *E. kartzoffiana*), *E. dunnii* and *Corymbia* spp.) and provenances. The results from the trials, along with information from the literature were incorporated into growth and damage models which were integrated with an economic model. Using a simulation approach, this system was used to investigate the economic cost of insect damage to *Eucalyptus grandis* and *E. globulus* plantations.

Results/Key findings

Levels of insect damage varied between sites, years and tree species. There was 0 to 54% defoliation per year. Within tree species, there was up to a three-fold difference in cumulative damage between provenances. Some provenances were resistant to autumn gum moth, but susceptible to leaf blister sawfly, or vice versa. There was a significant variation in tree growth between sites, irrespective of insect damage, and insect exclusion trials showed that some provenances performed better when sprayed while others did not.

This study tested a range of provenances at 1-3 sites per species (sites given below). The results indicate that some provenances perform better in terms of growth and insect resistance. However we caution that provenances may perform differently at other sites outside the study area. The key findings for each of the major tree species examined are listed below, followed by the results of the economic analysis.

E. grandis

Insect damage to this species was assessed at three irrigated sites at two localities, Mildura and Shepparton.

Damage

- Cumulative damage levels from trials at Mildura and Shepparton were moderately high.
- Six year old plantations incurred an 11% loss in tree volume due to insect damage.
- Mean volume loss between seed sources ranged from 7%–41%.

Major pests

- The major pest species were autumn gum moth (Mildura and Shepparton) and brown lace lerp (*Cardiaspina fiscella*) (Shepparton).

Resistance

- Cumulative damage levels varied by approximately 20% between seed sources.
- The most resistant seed sources were from Boambee (NSW), Lake Cathie (NSW) and Loxton selects (plantation selects from South Australia), while the least resistant seed sources were from Orara State Forest (NSW), Bruxner Park (NSW) and Coffs Harbour Seed Orchard. However all seed sources incurred very heavy damage (90%–100% defoliation) during the largest outbreak of autumn gum moth.

Provenance performance and management needs

- Taking into account both resistance and growth potential (in terms of plant volume), the seed sources with the best overall potential are Coffs Harbour Seed Orchard (Shepparton), Loxton selects and Pretoria (Mildura). Other seed sources with good potential include Pine Creek and Bruxner Park.
- Seed sources from Bulahdelah are predicted to perform well when the probability of insect damage occurring is low, while seed sources from Woondum and Boambee are predicted to perform well when the probability of insect damage occurring is high.
- Selection of a resistant seed source alone is insufficient to avoid economic losses from insect feeding in the event of a pest outbreak. Monitoring of pest numbers along with additional control measures such as the use of biological and chemical insecticides may be needed to optimise financial returns.

***E. benthamii* (including *E. dorrigoensis* and *E. kartzoffiana*)**

These species were examined at two irrigated seed orchard sites near Deniliquin, NSW. The seed orchards also included the *E. dunnii* and *C. maculata* provenances discussed below.

Damage

- High levels of defoliation (up to 84%) occurred in the final year of trials near Deniliquin. Subsequent assessment of the impact of damage on growth was not possible due to the end of the project.
- Single seed sources of the closely related *E. dorrigoensis* and *E. kartzoffiana* were more susceptible to autumn gum moth attack than *E. benthamii* and subsequently sustained higher levels of damage.

Major pests

- Autumn gum moth damage caused the high damage levels observed in the final year of assessment but leafblister sawfly was responsible for defoliation levels of up to 45% in younger trees.

Resistance

- These data are inconclusive as to whether there is significant insect resistance between *E. benthamii* provenances. Thus, the selection of material for planting should be based on other desirable characteristics such as growth rate and wood quality.

Provenance performance and management needs

- *E. kartzoffiana* and to a lesser extent *E. dorrigoensis* should not be planted where the probability of autumn gum moth damage is high.
- *E. benthamii* seed sources from Nepean River and Kedumba Valley have the best growth potential.
- High defoliation levels in the final year of the trial suggest that production losses due to insect damage are likely. Hence, it would be prudent to monitor pest numbers for timely application of control measures such as biological and chemical insecticides.

E. dunnii

This species was examined at two irrigated seed orchard sites near Deniliquin, NSW.

Damage

- Moderate to high levels of defoliation (up to 67%) occurred in the final year of trials near Deniliquin. Subsequent assessment of the impact of damage on growth was not possible due to the end of the project.

Major pests

- Autumn gum moth caused high damage levels in the final year while leafblister sawfly caused defoliation levels of up to 26% in younger trees.

Resistance

- These data are inconclusive as to whether there is insect resistance in *E. dunnii*. Thus, the selection of material for planting should be based on other desirable characteristics such as growth rate and wood quality.

Provenance performance and management needs

- Seed sources from Koreelah State Forest, Acacia Creek and Haystack East had the best growth.

- High defoliation levels in the final year of the trial suggest that losses due to insect damage are likely. Monitoring of pest numbers so that the timely application of control measures such as biological and chemical insecticides can occur, may be prudent.

***Corymbia* spp.**

This species was examined at two irrigated seed orchard sites near Deniliquin, NSW.

Damage

- Overall damage levels in the seed orchards near Deniliquin were uniformly very low to non-existent.

Provenance performance and management needs

- While exhibiting high levels of insect resistance, *Corymbia* spp. had slower growth rates than other species grown in the same locations (*E. dunnii* and *E. benthamii*) and it is therefore best suited to localities with a high risk of heavy insect attack.

E. globulus

This species was tested at one trial site in the ACT.

Damage

- Cumulative damage levels for the trial in the ACT ranged from low to moderately high.
- Five year old plantations incurred an 18% loss of growth due to insect damage.
- Mean volume loss between seed sources range from 0.5% to 56%.

Major pests

- The major pest species at the trial site was Christmas beetles (*Anoplognathus* spp.). Intense damage occurred over a short period (a few days to a few weeks) each summer.
- Less intense damage, caused by a number of other insect species, occurred for much longer periods (three months or longer) over the remainder of the year.

Resistance

- Cumulative damage levels varied by approximately 60% between seed sources.
- The most resistant seed sources were from Geeveston (Tasmania), Wee Jasper (NSW), Rylstone (NSW) and Beechworth (Victoria) while the least resistant seed sources were from St Mary's (Tasmania), Lorne (Victoria), Jeeralang (Victoria) and Mt Dromedary (NSW).
- Provenances from Tasmania and the Bass Strait islands, which have previously shown resistance to autumn gum moth and leafblister sawfly, also tended to show resistance to Christmas beetle (cross resistant).

Provenance performance and management needs

- Taking into account both resistance and growth potential (in terms of plant volume), Geeveston provenance had the best overall potential performance.
- Provenances from Traralgon (Victoria), Flinders Island (Bass Strait), and St. Mary's (Tasmania) are predicted to perform well when the probability of insect damage is low, while Black Range (NSW) is predicted to perform well when the probability of insect damage is high.
- Selection of a resistant seed source alone is insufficient to avoid economic losses from insect feeding in the event of a pest outbreak. Monitoring of pest numbers along with additional control measures such as the use of biological and chemical insecticides may be needed to optimise financial returns.

Economic analysis

Modelling indicated that the effect of insect damage was greater on *Eucalyptus globulus* plantations than *E. grandis* plantations. However simulations showed that while insect attack had a short-term impact on plantation standing volume, over the life of a plantation productivity tended to recover to pre-insect damage levels.

The extent of the recovery was thought to be a function of number of factors such as plant species, rotation time and silviculture practice. Specifically:

- *E. grandis* sawlog plantations on longer rotation times (~25 years) showed full recovery.
- *E. globulus* pulp plantations on shorter rotation times (~10 years for) showed only partial recovery and depending on the damage regime, this potentially caused a loss.

Insect monitoring had a variable impact on the internal rate of return (IRR) of simulated plantations:

- For longer rotation times such as sawlog plantations of *E. grandis* there was little impact.
- For shorter rotation times such as pulp plantation of *E. globulus*, impacts were larger

Adding insect control to monitoring had little impact on plantation IRR regardless of the management regime.

Recommendations for plantation management and research

- Most experiments to measure the impact of defoliation on plantation species report results for one or two growing seasons after damage. This gives information on resistance, but not tolerance. Future experiments need to be designed such that both types of response can be assessed.
- For fast-growing trees in resource-rich environments (good soil, suitable climatic range, adequate rainfall or irrigation) tolerance, rather than resistant to damage, may be a more useful approach in dealing with insect attack. This is an area of eucalypt biology that has been little studied and warrants further work for its potential as a management option.
- Development of decision support systems that allow economic analysis of changes in plant growth due to inputs such as environmental change and insect damage, should be considered. These would be a useful addition to the plantation manager's tool kit. Having the right information to make pest control decisions in the rapidly diversifying operating environment of plantation management is essential. The work done to develop the *Sylva Ento Model* used in this report could serve as a starting point for such a project.
- Development of biological control methods that either encourage or introduce natural enemies into a plantation at appropriate times should be considered. The former approach is likely to be more practical in the short-term. Research on encouraging natural enemies into plantations could look at the planting of other plant species as food sources or enhancing the structural or floristic diversity of plantations. These options would then need to be integrated with other silvicultural practices to ensure that plantation management is both cost-effective and practical.
- Silvicultural control is often overlooked when considered pest control options. It is possible that varying the spacing, pruning, fertiliser regime, thinning regime, weed control practice or layout of plantings could reduce the amount of insect damage in a plantation. The effects of these practices on key pest species are almost entirely unknown and warrant urgent attention.
- Monitoring the plantation for insect levels as part of routine plantation monitoring should make it as cost-effective as possible, and increase the manager's ability to decide timing and cost-effectiveness of insect control measures.

1 Introduction

Major research and tree establishment programs are being pursued in the Murray-Darling Basin and elsewhere, aimed at eucalypt plantations for landcare and commercial wood production. One of the regions being developed is the Murray Valley around Shepparton and Deniliquin. Some 100,000 ha of plantations are proposed for the area. The benefits of a forestry industry in the region are significant. An increasing proportion of farmland in the region is being degraded due to high watertable and salinity problems. Increasing the area committed to trees is likely to assist in ameliorating these problems (Nambiar *et al.* 2000). In recent years there has also been a decline of various rural industries and the establishment of alternative industries such as those using plantation timber products would greatly benefit the region. Eucalypt plantations are also being used to dispose of sewage effluent as part of an effort to phase out discharge of waste water into rivers.

The forest industry is also establishing a hardwood resource on farmlands to supplement supplies from native forests. Surveys of wood quality by CSIRO Forestry and Forest Products have indicated that high-grade products can be produced in irrigated plantations in the Murray Valley. The type of products envisaged for the area includes poles, pulp and paper products, composite boards and high-grade timber.

CSIRO Forestry and Forest Products has a comprehensive research program to support forest industry development, including tree growth and water use assessments, germplasm selection and seed orchards establishment in progress. When this program was being established it was recognised that insect herbivores could have a significant impact on plantations and retained woodland. Many young plantations in the Murray Valley had incurred heavy defoliation from a range of insects including leafblister sawfly (*Phylacteophaga* spp. (Hymenoptera: Pergidae)), autumn gum moth (*Mnesampela privata* Guenée (Lepidoptera: Geometridae)), and a number of psyllid species (*Cardiaspina* spp. (Hemiptera: Psylloidea)). The two most commonly planted species of eucalypts, *E. grandis* Hill ex Maiden and *E. globulus* Labill., are quite susceptible to insect feeding and have suffered high levels of mortality at a number of sites. A number of the older plantations had also suffered damaged by borers (*Phoracantha* spp. (Coleoptera: Cerambycidae)).

Understanding what causes insects to reach levels where they become pests is of fundamental importance in preventing or managing damage. Knowing why the numbers of a pest species increase may allow the development of strategies that prevent such increases occurring, or may allow the level of damage to be contained or reduced. One common thread that links many of the factors that contribute to pest outbreaks is the provision of a large quantity of high quality food and/or breeding sites for herbivorous insects (Speight 1997) often in conjunction with an absence of, or reduced incidence of, natural enemies.

In natural ecosystems, destructive outbreaks of insect herbivores are rare (Hartley and Jones 1997). The terrestrial world is green and tends to stay that way (Hairston *et al.* 1960). In general, plants are poor insect food because, in the terminology of Hartley and Jones (1997), they mostly contain 'cruddy' ingredients. 'Cruddy' ingredients either reduce the nutritional quality of plant material or inhibit a herbivore's ability to obtain nutrients. Examples of 'cruddy' ingredients are tough fibres, high carbohydrate and cellulose content, low nitrogen, toxins and digestibility-reducing substances. So finding suitable food among all the unsuitable material in a natural system is difficult for herbivores. Plant characteristics are intrinsically heterogeneous in space and time and vary continuously in response to the environment. Also the poor food quality of plants may influence the extent to which natural enemies control herbivore populations.

Intensive production systems whether they are agriculture, horticulture or forestry, almost invariably represent a large scale departure from the natural habitats in which the pest species evolved. They also remove a large proportion of the natural heterogeneity that may inhibit herbivores finding suitable food. This often leads to changes in the ecology of the pest species.

Not all herbivory is equally damaging to a plant. The timing (phenology), plant part (what is attacked and its age), intensity (how much is eaten) and frequency (how often attacks occur) all influence the impact of herbivory (Crawley 1997). Understanding how all these factors interact is important when designing a management program for pests.

Also, individual plants are not all equally susceptible to a given level of damage. Two distinct ecological features influence the susceptibility of a plant to its herbivores. These are environmentally determined changes in the host, and genetically controlled mechanisms of resistance which can be passed onto subsequent generations in selection and breeding programs (Speight *et al.* 1999). The conditions in which a plant grows are fundamental to determining its vigour. Plants that are stressed tend to show enhanced levels of nitrogen and reduced levels of physical and chemical defences (White 1993), making them more susceptible to certain types of insect attack. Boring and sucking insects seem to perform better on stressed plants, while gall-formers and chewers perform less well (Koricheva *et al.* 1998). Stone and Bacon (1994b) found a significant correlation between plant growth parameters, water stress and insect damage in a native forest of *E. camaldulensis* Dehnh. In intensively managed agroforestry or farm forestry systems, good silvicultural techniques should generally reduce environmental stress.

Genetic or inherited resistance occurs when certain genotype-based characteristics enable a plant to reduce or tolerate the impact of insect feeding. Breeding programs attempt to isolate the germplasm containing these characteristics that then can be incorporated into new resistant strains. The mechanisms of genetic resistance are normally grouped under three headings: non-preference (antixenosis), antibiosis (for instance, lower fecundity) and tolerance (Horber 1980; Painter 1951). Non-preference or antixenosis occurs when insects tend to avoid or reduce their feeding rate on one species or genotype. Antibiosis mechanisms can either be physical or chemical. They may act on the insect performance as much as to stop it feeding in the first place. Physical defence mechanisms can take the form of tough or hairy leaves, tough indigestible fibres in leaves or stems or waxy substances that inhibit insect movement around the plant. Chemical mechanisms can either be nutritional or defensive or a combination. Finally some plants continue to grow well and provide high yields even when sustaining damage levels that decrease yields in other genotypes, i.e. tolerance.

Previously there had been no studies that quantified the impact of insect damage on the rate of production of eucalypt plantation in the Murray Valley, even though severe defoliation by insects has occurred in a number of plantations (Neumann and Collett 1992). The role of resistance in plantation pest management has been reviewed by Floyd and Farrow (1994), and preliminary observations on relative resistance of provenances of *E. camaldulensis* and *E. globulus* in the Murray Valley have been reported (Farrow *et al.* 1994; Floyd *et al.* 1994).

The main aims of this study were to:

1. Assess provenances and families of several species of eucalypts for resistance to pests of young trees in order to incorporate resistance into breeding programs in seed orchards
2. Measure the impact of insect feeding on the growth and form of young eucalypts in existing and new plantations established under irrigation or high water table sites in the Murray Valley and to incorporate this information into growth and damage models
3. Develop a set of recommendations for the environmentally sensitive management of insect pests involving insect resistance in young trees for use in farm forestry.
4. Evaluate the economic cost of insect damage within plantations in the Murray Valley through modelling management scenarios

To achieve these outcomes, a number of existing and new trials were used. These trials were located at sites in and around Canberra, Deniliquin, Shepparton and Mildura (Figure 1.1). Material examined included provenances and seedlots of the following species:

- *Corymbia henryi* Blake,
- *C. maculata* Hook.,
- *C. variegata* (Hook.) Hill & Johnson,
- *E. benthamii* Maiden & Cambage,
- *E. dorrigoensis* (Blakely) Johnson & Hill,
- *E. kartzoffiana* L. Johnson & Blaxell,
- *E. dunnii* Maiden,
- *E. globulus*
- *E. grandis*.

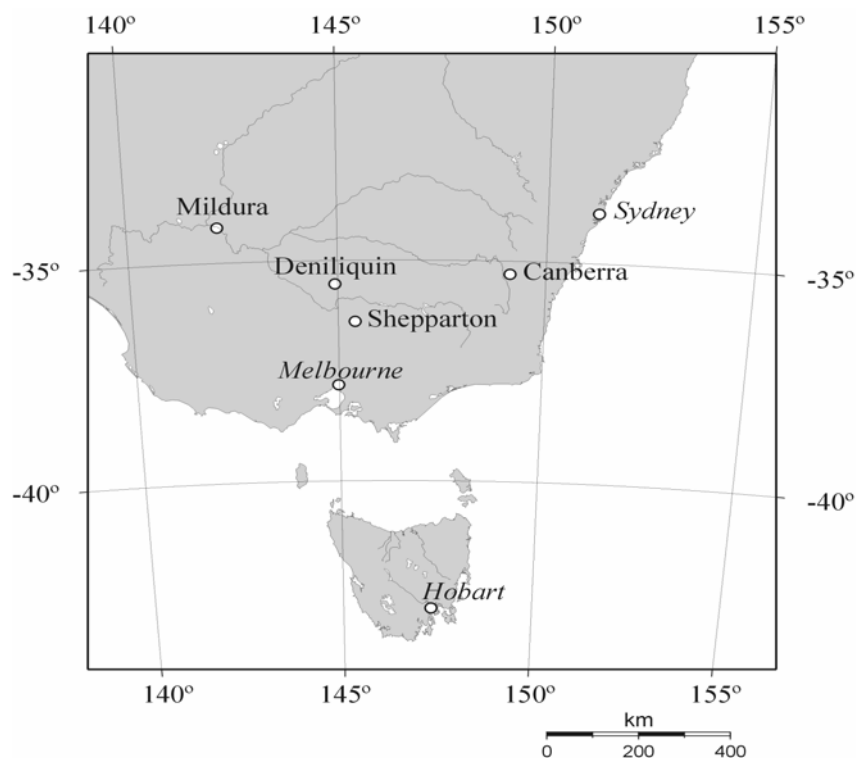


Figure 1.1 Map showing location of trial sites

We have organised the results of this study into discrete chapters. Except for Chapter 6, each has an introduction, material and methods, results and discussion. References from all chapters are listed at the end of the report.

Results of field trials are reported in Chapters 2–5. Each of these chapters either reports results for a single tree species or a discrete field site. Data on the phenology and biology of the major pest species observed in the studies are presented in Chapter 6. Chapter 7 presents an economic analysis of the impact of insect damage and uses data from various sources including the previous chapters and the literature. A general discussion and summary of the results is provided in Chapter 8.

2 Within species variation in insect damage and growth in *Eucalyptus grandis*

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Summary

Within and between provenance variation in susceptibility to insect damage of *Eucalyptus grandis* Hill ex Maiden and the relationship between insect damage and tree growth was investigated. The growth and insect damage was measured on 16 seedlots of native provenances and genetically improved material of *E. grandis* at three irrigated sites at two localities (Shepparton and Mildura) in the Murray Valley.

Autumn gum moth (*Mnesampela privata* (Guenée)) and brown lace lerp (*Cardiaspina fiscella* Taylor) were the dominant herbivores during the trials. Mean annual defoliation at Shepparton was low to moderate, ranging from $2.2\% \pm 0.56\%$ to $54.0\% \pm 0.67\%$ (Mean $\pm$ SE). Autumn gum moth defoliation at Mildura was initially low ($\leq 6.0\%$), became very high (80–100%) later in the trial.

Insect damage reduced plant performance at both localities, although its impact on *E. grandis* provenances varied between localities and between sites within a locality. At Shepparton the most resistant seedlots were the native provenances, mainly from the Coffs Harbour region. However, when both growth and potential insect damage were considered together, the genetically improved material from the Coffs Harbour Seed Orchard was predicted to be the seedlot with the greatest growth rate. At Mildura there was a significant interaction between site and seedlot variation in the analysis of tree volumes. Overall, growth was best in the genetically improved seedlots from Loxton (South Australia) and Pretoria (South Africa). The best natural provenance was again from the Coffs Harbour region. All seedlots at Mildura incurred high levels of autumn gum moth damage, causing mortality of the smaller trees. No evidence of cross-resistance to the dominant insect herbivores of the study was found.

Introduction

Eucalyptus grandis Hill ex Maiden is among the most widely planted eucalypts around the world (Burgess 1988). Interest in its use as a plantation species developed in the late 1960s and early 1970s although this interest waned by the mid 70s. In the 1990s interest in the species was again high. Recent work has identified *E. grandis* as the best eucalypt species for fast growing pulpwood plantations over a wide range of coastal Queensland (Cromer *et al.* 1991). The species is now also one of the key parent species from which hybrid combinations of eucalypts are being developed for farm forestry (Harwood and Arnold 1999).

The impact of insect herbivory on growth potential and form of *E. grandis* plantations in Australia has occasionally been a significant concern. Wingless grasshopper (*Phaulacridium vittatum* (Sjöstedt) Orthoptera: Acrididae) and various melalonthine beetles have caused damage to trees at establishment, while a range of insects have caused significant damage to saplings and trees. Among the most important insect pests of established *E. grandis* are autumn gum moth (*Mnesampela privata* (Guenée) Lepidoptera: Geometridae), leafblister sawfly (*Phylacteophaga* spp. Hymenoptera: Pergidae), brown lace lerp (*Cardiaspina fiscella* Taylor Hemiptera: Psyllidae) and gumtree scale (*Eriococcus coriaceus* Maskell Hemiptera: Eriocidae). The establishment pests and gumtree scale can kill whole plants, while other pests may affect growth increment, but rarely cause mortality.

Early provenance trials in Australia centred on the Coffs Harbour region of NSW and in the mid 80s at Peachester in Queensland (Burgess 1988). More recent trials have been established under irrigation in the southern Murray Darling Basin (Arnold *et al.* 1996) and at Dubbo in central NSW (Burgess 1988).

These trials, along with numerous international studies have shown some of the most productive provenances are those from northern NSW, centred around Coffs Harbour (Burgess 1988; CABI 1998). However, in any one location, other provenances from disparate areas of the species natural range also tend to perform well (CABI 1998). Additionally, significant differences in growth performance have often been noted between seedlots of the species obtained from one small geographical area (Arnold *et al.* 1996; Burgess 1988; CABI 1998; Eldridge *et al.* 1993; Matheson and Mullin 1987).

One factor that may contribute to variation between growth and form of *E. grandis* when planted in southern Australia is genetic variation in susceptibility to insect damage (Floyd and Farrow 1994). A number of provenances of other species of eucalypts have been identified as having superior resistance to defoliating insect pests (Farrow *et al.* 1994; Floyd *et al.* 1994). Appropriately deployed as part of good silvicultural practices, provenances with insect resistance increased through selection and breeding can provide an environmentally sensitive approach to pest management.

In 1993–94 three provenances-family trials at two sites were established across a range of effluent irrigated sites in south eastern Australia to evaluate natural provenances and seed orchard seedlots. These trials were established to identify seedlots of *E. grandis* with superior resistance to insect attack and provide a base from which to select more resistant material for breeding. This chapter reports on between-provenance variation in growth at the two sites after seven years and the interaction of this variation with levels of insect damage.

Materials and methods

Site description and preparation

Shepparton

The trial was located 10 km from Shepparton township within Daldy Road Farm belonging to Goulburn Valley Water (36° 19' 13.5"S 145° 23' 25.1"E, and 113 m a.s.l.). Soils types are Goulburn Loam and Congupna Clay Loam and are categorised as grey-brown clay loams at 0–15 cm overlaying yellow-grey medium and heavy clays to 200 cm. The clay subsoils are dense and intractable and not a good medium for roots. Soils analysis revealed mean surface (to 25 cm) - pH (H₂O) of 6.6 and pH (CaCl₂) of 5.9. Deeper profiles from 25 to 200 cm ranged from - pH (H₂O) of 7.5 to 8.3 and pH (CaCl₂) of 6.7 to 7.5. Site preparation involved ripping to a depth of 60 cm followed by the application of gypsum at a rate of 5 ton/ha. Ripping was done using a “winged foot” ripper behind a bulldozer. This approach effectively lifts and shatters the entire clay profile and is preferable to the use of a single tyne ripper along the intended tree row which tends to cause compaction in heavy soils. The trial was trickle irrigated with primary treated domestic and industrial waste water from the Shepparton/Maroopna region. The trees received in the order of 7 megalitre/ha/annum of irrigation water. Trees were planted on a 3 x 2 m grid on an East West alignment. Planting occurred from 23/11/1993 to 4/12/1993.

Mildura

The two sites at Mildura (Mildura-A—34° 20' 4.4"S 142° 04' 36.9"E and Mildura-B—34° 20' 9.0"S 142° 04' 17.2"E, 30m a.s.l.) were located at the Koorlong Wastewater Treatment and Reuse Centre. The treatment plant is approximately 6.5 km from the Koorlong township and approximately 18 km from the Mildura township. The sites are part of a 105 ha waste water drip-irrigated hardwood species

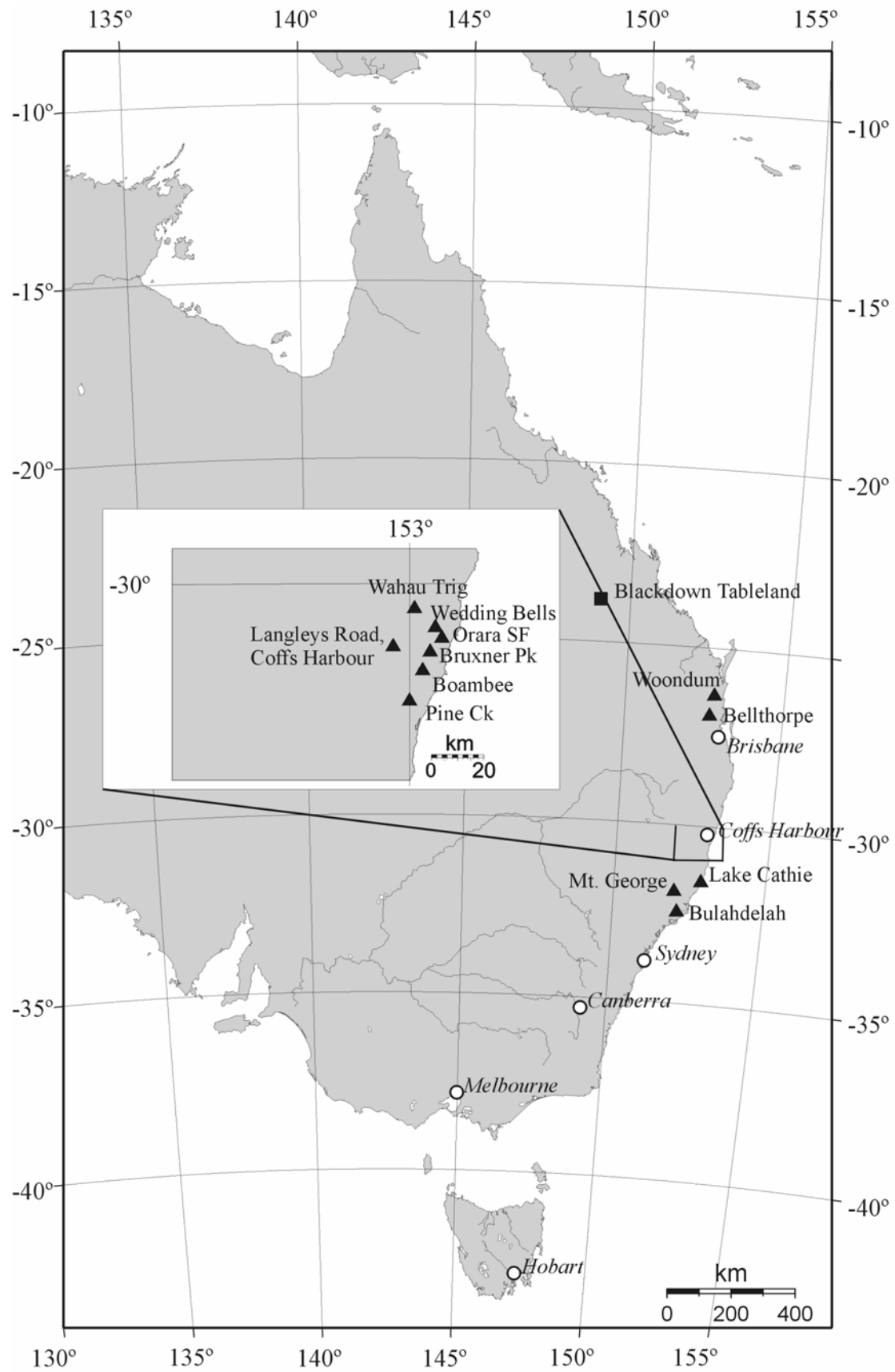


Figure 2.1 Localities of Australian unimproved natural provenances of *E. grandis* (▲) and *E. saligna* (■) used in the trials. Details of each provenance are given in Table 2.1.

Table 2.1 Details of the *Eucalyptus grandis* and *E. saligna* seedlots established in the trials at Mildura and Shepparton

CSIRO Seedlot No.	Species	No. of parent trees in bulk lot	Provenance details				No. of seedlots at each site					
			Location	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	Mildura-A		Mildura-B		Shepparton	
							Bulk	Individ.	Bulk	Individ.	Bulk	Individ.
11159	<i>E. grandis</i>	4	Mt. George, NSW	31° 50'	152° 00'	300	1	0	1	0	0	0
11996	<i>E. grandis</i>	6	Bulahdelah, NSW	32° 25'	152° 10'	200	1	0	1	0	1	0
15120	<i>E. grandis</i>	10	Lake Cathie, NSW	31° 32'	152° 52'	10	1	0	1	0	1	0
15632	<i>E. grandis</i>	8	Woondum, QLD	26° 17'	152° 48'	100	1	0	1	0	1	0
16435	<i>E. grandis</i>	8	Wedding Bells SF, NSW	30° 09'	153° 07'	120	1	4	1	4	0	5
16437	<i>E. grandis</i>	15	Wahau Trig, NSW	30° 05'	153° 01'	300	1	5	1	5	0	6
16439	<i>E. grandis</i>	12	Orara SF, NSW	30° 11'	153° 08'	3	1	0	1	0	0	0
16442	<i>E. grandis</i>	-	Bruxner Park, NSW	30° 14'	153° 05'	200	0	5	0	5	0	6
16454	<i>E. grandis</i>	-	Pine Creek SF, NSW	30° 24'	153° 00'	150	0	6	0	6	0	5
16447	<i>E. grandis</i>	-	Langley's Rd, Coffs Harbour, NSW	30° 13'	152° 56'	630	0	6	0	6	0	6
18277	<i>E. grandis</i>	-	Bellthorpe, QLD	26° 52'	152° 42'	400	0	6	0	6	0	6
ERA-1 ¹	<i>E. grandis</i>	1	Boambee, NSW	30° 18'	153° 03'	60	0	0	0	0	1	0
ERA-2 ¹	<i>E. grandis</i>	100	Loxton, SA (plantation selects)	34° 26'	140° 36'	30	1	0	1	0	0	0
18146	<i>E. grandis</i>	> 24 ²	Coffs Harbour Seedling Seed Orchard (SFNSW)	30° 08'	153° 07'	100	1	0	1	0	1	0
17803	<i>E. grandis</i>	Bulk ³	Clonal Seed Orchard, Pretoria, SOUTH AFRICA	--	--	--	1	0	1	0	0	0
18229	<i>E. saligna</i>	-	Blackdown Tableland, QLD	23° 50'	149° 05'	880	0	6	0	6	0	6
TOTALS:							38		38		40	
Number of seedlots							10		10		5	
Number of provenances							14		14		12	

1 These seedlots were not obtained through CSIRO.

2 The Coffs Harbour Seedling Seed Orchard seedlot comprised a multiple parent bulk seedlot made up of seed from 3 to 4 parent trees of each of the 24 families in the State Forests of NSW (SFNSW) seed orchard at the time of collection.

3 This seedlot consists of an imported multiple parent bulk seedlot from a clonal seed orchard (number of parent trees uncertain) in South Africa.

of *Eucalyptus* (including various provenances of *E. grandis*) and swamp sheoaks, *Casuarina glauca* Sieb ex Spreng. (Casuarinaceae). Trees are planted in 50 modules ranging in size from approximately 1 ha to 18 ha. The irrigation water was treated domestic and industrial waste from the Mildura/Irrempole region and the functional units of control for irrigation are the modules. The trial modules were irrigated all year around receiving a yearly average of 7.6 megalitre/ha (5.05–9.40 megalitre/ha) of water (excluding rainfall) which, in all years except the drought of 1997–98, was adequate for plant growth. Mildura-A is located in module 24, a free draining site with a deep sandy loam (of 30 to 60 cm depth) overlying a clay formation, while Mildura-B is in module 30, which has a heavier clay loam soil. Prior to establishment of the trials both sites were relatively alkaline (pH 8.0 to 8.5). Site preparation consisted of ripping of planting lines to 60 cm depth and treatment of planting lines with pre-emergent herbicides. Tree spacing at sites A and B was 3 x 2 m and planting occurred from 13/12/1993 to 14/12/1993. The only post planting maintenance was slashing every three months to control for weeds and to easy access to the modules for assessment.

Study organism

Eucalyptus grandis is one of the most widely planted eucalypts around the world (Burgess 1988). In Australia it naturally occurs between latitudes 17° S (Windsor Tablelands, QLD) and 32° S (near Newcastle, central NSW) and within 100 km of the eastern coast. At each of the sites where plantations were established a total of 47 seedlots representing 15 different provenances were planted. Additionally six seedlots of a single provenance of *E. saligna* Smith were also planted as, at the time, they were thought to be *E. grandis* (Table 2.1 and Figure 2.1).

The major pest species during the trials were autumn gum moth, *Mnesampela privata* (Guenée). (Lepidoptera: Geometridae), the brown lace lerp and leafblister sawfly, *Phylacteophaga* spp. (Hymenoptera: Pergidae). All three can cause severe defoliation of plants. Larvae of autumn gum moth and leafblister sawfly chew the leaves, reducing photosynthetic area both by directly removing leaf tissues and indirectly by causing leaf fall of damaged leaves. The brown lace lerp is a sucking insect and causes leaf necrosis due to the toxic nature of the saliva injected into the leaves. Photosynthetic efficiency is hindered by the necrosis and at high densities the psyllids cause leaf fall. The large volume of fluid removed from the plant through psyllid feeding can cause water stress during high density infestations.

Site layout

The two Koorlong trials and the one at Shepparton each comprised five complete replicates with rows and columns within replicates providing two-dimensional blocking within replicates. The seedlots in each trial were represented as 4-tree row plots in each of six replicates. Buffers of one to three rows of trees were planted around the experimental blocks. A sixth replicate at both Mildura and Shepparton was designed as an insect exclusion replicate. The replicate was divided into two compartments, one to receive regular insecticide applications, the other to be left unsprayed. Insect damage in the first few years at Mildura was very low so no spraying was carried out. At Shepparton spraying of replicate six was carried out through out the life of the trial. Only a subset of provenances was used in this replicate and they were Blackdown Tableland, Bulahdelah, Coffs Harbour Seed Orchard, Langleys Road and Pine Creek. In mid 1996 two additional replications were included in the spraying program to help monitor the impacts of an outbreak of lerp forming psyllids. Each of these replicates contained the full complement of 12 provenances in the trial.

At Koorlong in 1997 additional sites in each of eight modules outside of the two trial blocks were established to help monitor the development of an autumn gum moth outbreak. Eight modules of *E. grandis* were selected and within each module, a block of trees of the same seedlot (ERA-2, Table 2.1) were marked. The number of trees in each site varied between modules, depending on the layout and totalled either 20 or 36. Modules were selected to give as wide and even coverage over the

site as possible. Subsequently spraying for autumn gum moth control occurred in the modules containing six of the additional eight sites in 1998 and in all modules containing additional sites in 1999. The insecticide used was MIMIC™. Performance of trees in these monitoring sites was compared with trees of the same seedlot in the two unsprayed trial modules.

Measurements

Plant growth and the level and type of insect damage were regularly measured at all sites. Annual measurements of growth and insect damage were made during mid to late winter (June-August) when tree growth was minimal. Depending on the level of activity of herbivorous insects, additional damage measurements were made as appropriate through out the year. The autumn gum moth monitoring sites were visited from 1998 onwards at approximately monthly intervals from February to May, corresponding with oviposition and early instar development. Exact timing and frequency of visits depended on the development of the autumn gum moth population. The impact of autumn gum moth feeding was measured as part of the annual winter assessments.

Insect damage

The extent of all plant damage, including insect damage, was visually assessed with damage levels for each source recorded separately. To ensure consistency the same observers conducted all damage estimates. Damage levels were scored as percentages on a scale from 0–100% in 10% intervals between 10% and 90% and with finer graduations near 0% and 100% (0%, 1%, 5% and 95%, 99%). Separately assessing damage by different insect species was possible because each insect produced characteristic damage. Where appropriate separate damage assessments were made for different parts of the plant (e.g. foliage, stems) and different stages of development (e.g. immature foliage vs mature foliage). During autumn gum moth oviposition (February to May), numbers and sizes of autumn gum moth egg batches and larvae were also recorded. Cumulative damage, the total damage load an individual or seedlot incurred over the trial, was calculated by summing annual percentage damage.

Plant growth

The height and diameter of each plant were used as measures of plant growth. Initially tree height was measured to the nearest 0.1 m using graduated height poles. As the plantations developed this became impractical and the poles were replaced with an electronic measuring device (VERTEX). The standard measure of tree girth was diameter at breast height (DBH) which is defined as the diameter at 1.3 m above ground level. However, this was only practical when trees were at least 2–2.5 m tall. As we were interested in detecting long-term impacts of insect damage on young trees it was necessary to measure tree diameter at least annually from the time the trees were planted. When trees were too small for DBH measurements, diameter at ground level (DGL) was used as an alternative. Individual tree volume (V in dm^3) was calculated using the conical volume equation:

$$V = \frac{(DBH / 2)^2 \times Ht \times \pi}{3 \times 100^3}$$

where Ht = height in mm and DBH is diameter at breast height in mm. Only a subset of trees was included in the volume calculations. Trees with multiple trunks or trees that had suffered substantial trunk or crown damage were excluded, as the conical equation is not a good estimator of volume for these trees. Furthermore in commercial plantations these trees would normally be thinned as part of routine maintenance. Relative growth rates (RGR in $\text{dm}^3 \text{dm}^{-3} \text{yr}^{-1}$) of plants, corrected for the initial plant size, was calculated as:

$$RGR = 365 \times \frac{V_{t_{+1}} - V_t}{V_t \times (t_{+1} - t)}$$

where V_t and V_{t+1} are square root transformations of volume at time t and $t+1$ respectively and t = date of initial measurement and $t+1$ = date of final measurement.

Analysis

Shepparton

The trial was originally designed to look at provenance performance and damage and as outlined above only replicate 6 was sprayed from the start. Other sprayed replicates were added after an outbreak of brown lace lerp on the plantation in 1996 (see above). This unbalanced the experimental design and we therefore used restricted maximum likelihood analysis (REML: Corbeil and Searle (1976)) instead of ANOVA to examine the effects of spraying and differences among provenances on plant growth and levels of insect damage. Significance was tested using a likelihood ratio test based on the difference (Δdev) between log-likelihoods calculated for a full model, which included all terms, and a nested sub model from which the terms of interest were dropped (Genstat 5 Committee 1993).

There were significant differences between the size of provenances at planting and plant initial volume was used as a covariate in the analysis of pre-1996 data. To control for the impact of insect damage prior to the July 1996 spraying, initial plant volume was subtracted from the 1996 winter assessment volume and the result used as a covariate in analysis of post 1996 data. Regression was used to examine the relationship between plant growth among provenances and insect damage levels. All statistical analyses were performed using Genstat (Genstat 5 Committee 1993).

To examine how seedlots would perform under different levels of insect damage, the growth data was used to calculate predicted plant volumes ($V_{(p)}$) for different values of p (the probability of occurrence of insect damage) for each seedlot using the formula:

$$V_{(p)} = \frac{V_u \times p + V_s \times (1 - p)}{2}$$

where V_u = mean volume of unsprayed plants and V_s = mean volume of sprayed plants.

Mildura

We examined the effects of spraying insecticide and the differences among provenances in growth and insect damage. As there was no insecticide treatment applied to the trial plantations, we examined growth rates by comparing plants in the sprayed autumn gum moth monitoring site to those of the same provenance in the trial sites and the unsprayed monitoring sites. As the study progressed, it became apparent that the growth rate of plants in the Mildura-B site was greater than that of plants in Mildura-A. The Mildura-A site was planted on the side of a ridge and it also became apparent that there were differences in the rate of plant growth at the top and bottom of the ridge. To control for site differences we used REML to examine differences in plant growth among provenances in the trial sites and to estimate mean growth rates of plants for each population. Regression was used to examine the relationship between insect damage levels and plant growth among provenances. All statistical analyses were performed using Genstat (Genstat 5 Committee 1993).

Results

Insect damage

Shepparton

Damage levels were moderate to low through out the trial, although in all years at least some trees sustained between 80% and 100% defoliation (Table 2.2). The highest damage levels were in 1996 ($54.0\pm0.67\%$ (0%–90%)) and the lowest in 1999 ($2.2\pm0.56\%$ (0%–100%)). Over 95% of the insect damage at Shepparton was caused by two species—autumn gum moth (41.4%) and lerp-forming psyllids (53.7%). Autumn gum moth damage occurred throughout the trial (mean annual damage = 11.0%, range of annual damage = 1.2%–49.4%), although the most damage occurred in the first year (49.4%). Lerp damage was low in the first two years (0% in 1994, 1.1% in 1995), peaked in 1996 (50.9%) and then declined to low levels for the remainder of the trial (mean annual damage = 10.0%, range of annual damage = 0–14.4%).

Table 2.2 Summary of percentage defoliation caused by insect attack at Shepparton and Mildura. Mean $\pm$ SE (range)

Sample	Mildura				Sample	Shepparton	
	A		B				
Nov 1994	3.3±0.22	(0–100)	0.9±0.08	(0–30)	Aug 1994	49.5±1.25	(0–100)
July 1995	0.7±0.13	(0–60)	0.2±0.08	(0–50)	Aug 1995	10.1±0.39	(0–90)
July 1996	0.6±0.17	(0–70)	0.1±0.05	(0–50)	Nov 1995	33.7±6.22	(0–100)
Aug 1997	6.0±0.36	(0–100)	2.9±0.29	(0–100)	April 1996	54.0±0.67	(0–90)
July 1998	100.0±0.0		99.1±0.15	(60–100)	Aug 1996	35.8±0.92	(0–100)
Aug 1999	80.8±0.87	(0–100)	79.3±0.87	(0–100)	April 1997	21.0±0.88	(0–80)
Aug 2000	20.6±1.08	(0–100)	6.4±0.54	(0–100)	June 1997	16.6±0.85	(0–100)
					Aug 1997	36.2±1.03	(0–100)
					Aug 1998	33.4±1.11	(0–100)
					Aug 1999	2.2±0.56	(0–100)

Cumulative damage was generally even across the 14 provenances of *E. grandis* and *E. saligna* in the study (Figure 2.2a). Boambee was the most resistant provenance (214%), while Bruxner Park (263.9%) and Coffs Harbour Seed Orchard (262%) were the least resistant *E. grandis* seedlots. The *E. saligna* seedlot, Blackdown Tableland, was the last resistant of all the seedlots (274%). Overall there was only a 20% difference between the most resistant and least resistant provenances.

Damage by autumn gum moth and brown lace lerp between provenances was more variable (Figures 2.2b and 2.2c) with near to a two-fold difference in cumulative damage among the 14 *E. grandis* provenances. Autumn gum moth damage was greatest on trees from the Lake Cathie provenance (127.3%) and least on trees from the Woondum provenance (74.9%), while brown lace lerp damage was greatest for trees from the Coffs Harbour Seed Orchard improved seedlot (122.3%) and least on trees from the Lake Cathie provenance (78.4%). The *E. saligna* seedlot, Blackdown Tableland, had the highest level of brown lace lerp damage of all seedlots (137.8%). Also, provenance showed a negative correlation between resistant to damage by the two species of insect herbivores ($r = -0.603$). Provenances with a greater resistance to one insect species tended to be more susceptible to the other species. For example, the Lake Cathie provenance had the lowest cumulative psyllid damage level (79%), but the highest level of cumulative autumn gum moth damage (127.3%). The *E. saligna* provenance, Blackdown Tableland, had the highest level of cumulative psyllid damage (137.8%) but the second lowest level of cumulative autumn gum moth damage (76.4%). There was little variation among the 14 provenances in the pattern of autumn gum moth and psyllid damage over time. The only exception was autumn gum moth damage to the *E. saligna* provenance, Blackdown Tableland. It

suffered little damage in 1994 when the greatest damage by this insect was occurring to the other provenances (Figure 2.2b). However, in 1997 during a second, but less severe episode of attack by autumn gum moth, it suffered the highest level of damage among the provenances.

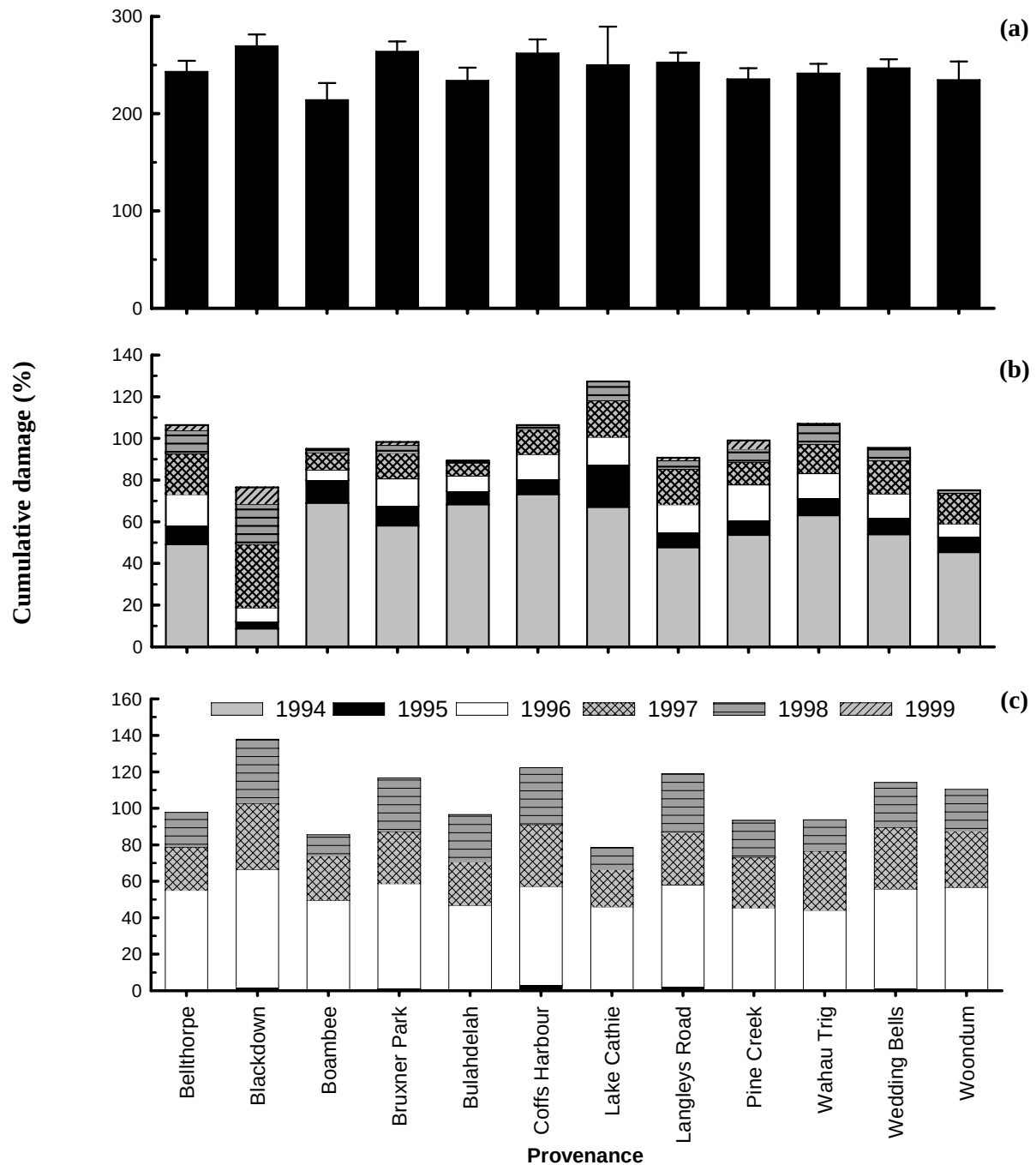


Figure 2.2 Insect damage incurred by 12 seedlots of *Eucalyptus grandis* and one provenance of *E. saligna* at Shepparton from 1993–1999. (a) Cumulative damage for all insects (Mean $\pm$ SE), (b) Autumn gum moth damage by year and (c) Brown lace lerp damage by year. There was no brown lace lerp damage in 1994 and 1999 and damage in 1995 was minimal (0.0%–2.1%).

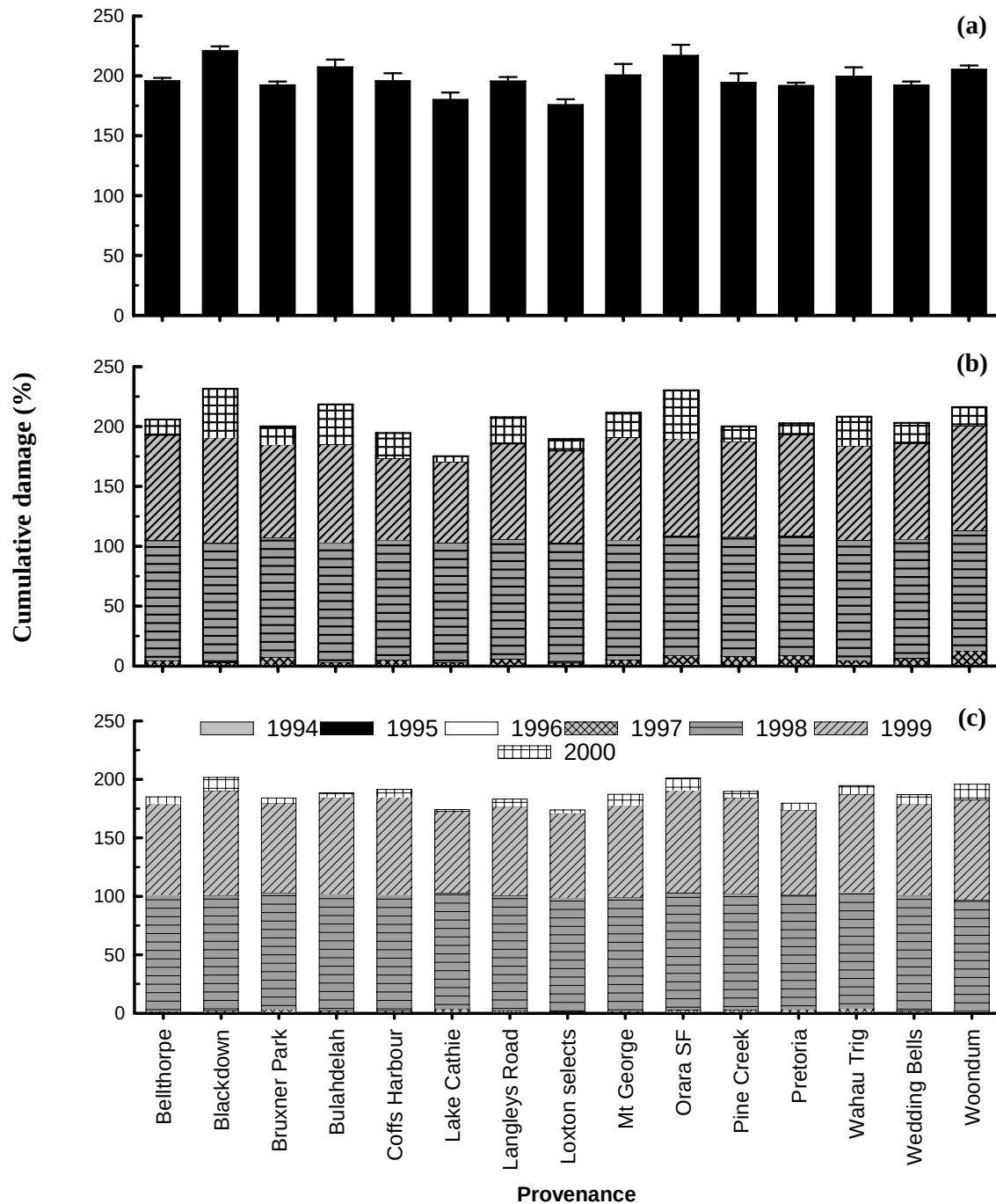


Figure 2.3 Insect damage received by 14 seedlots of *Eucalyptus grandis* and one seedlot of *E. saligna* at Mildura from 1994–2000. (a) Cumulative damage for Mildura-A and Mildura-B combined (Mean $\pm$ SE), (b) Autumn gum moth damage by year for Mildura-A and (c) Autumn gum moth damage by year for Mildura-B. There was no autumn gum moth damage for the period 1994–1996

Mildura

For the first four years of the Mildura trial insect damage was minimal (Table 2.2). In 1998 an outbreak of autumn gum moth almost completely defoliated both sites. All 3808 live plants in the two trials were affected with mean damage in excess of 99%. High levels of autumn gum moth damage also occurred in 1999, but by 2000 damage levels had tapered off with only minimal damage at Mildura-B and low to moderate damage at Mildura-A.

The uniformly high levels of autumn gum moth damage in 1998–99 are reflected in the mean cumulative damage levels across the 14 provenances (Figure 2.3a). There was little difference between the most susceptible provenances (Blackdown Tableland, 216.7% SD = 46.4% and Orara SF, 213.2% SD = 35.5%) and most resistant provenances (Loxton selects, 178% SD = 34.4% and Lake Cathie, 178.3% SD = 32.2%). Variation in levels of autumn gum moth damage among provenances in 1998 and 1999 was minimal (Figures 2.3b and c). The only noticeable variation was in 2000 at Mildura-A where mean cumulative damage levels between provenances ranged from 4.4% (Lake Cathie, SD = 14%, n = 18) to 40% (Blackdown Tableland, SD = 40%, n = 101) (Figure 2.3b).

Plant growth

Shepparton

Over the period of the trial insect damage did reduce plant volume (Figure 2.4) (REML testing for the overall effect of spraying: $\Delta\text{dev} = 13.71$, $\text{df} = 1$, $P < 0.001$). Due to damage by insecticides, mean plant growth tended to be greater in the unsprayed treatment early in the experiment when insect damage was low. However, as damage increased due to lerp activity in 1996–97 (Table 2.2), this trend reversed and growth rates in the sprayed treatment were greater.

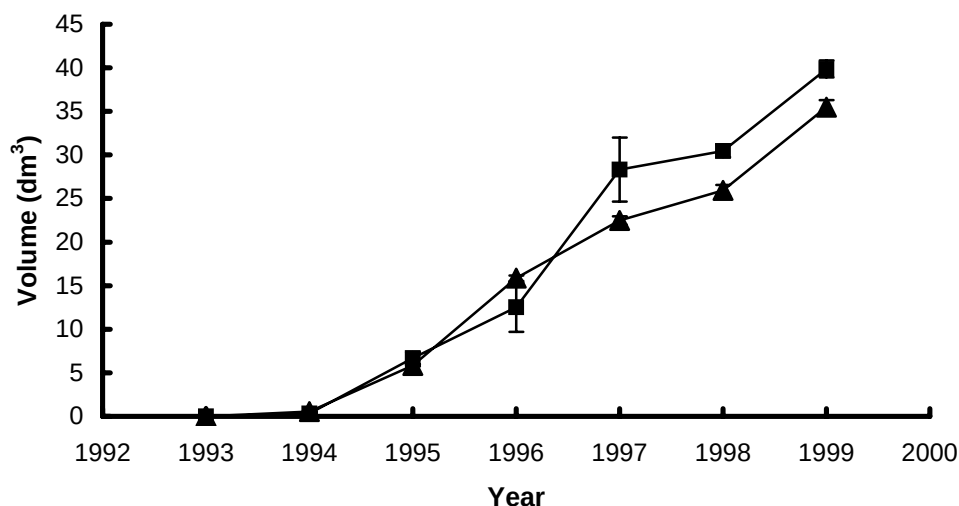


Figure 2.4 Growth of *Eucalyptus grandis* sprayed (■) and unsprayed (▲) treatments at Shepparton (Mean $\pm$ SE).

Growth varied among the 12 provenances of *E. grandis* and *E. saligna* at Shepparton (Figure 2.5) with almost a two fold difference in mean volume of sprayed plants. These inherent differences in volume were significantly different (REML testing for provenance effect: $\Delta\text{dev} = 57.93$, $\text{df} = 11$, $P < 0.001$). The top three provenances with largest volumes were Bulahdelah, Coffs Harbour Seed Orchard and Lake Cathie (Table 2.3). Variation in volume among the unsprayed plants was equivalent in magnitude, but relative performance of the various provenances differed. The top three provenances with largest volumes among the unsprayed plants were Boambee, Pine Creek and Woondum (Table 2.3).

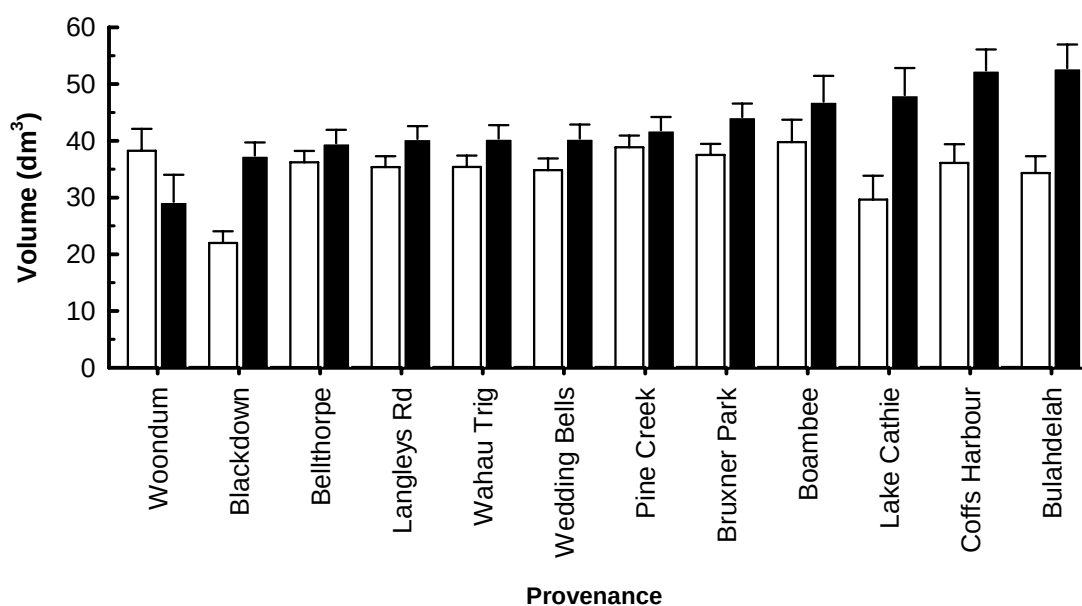


Figure 2.5 REML estimates of tree volume of 12 seedlots of *Eucalyptus grandis* and one provenance of *E. saligna* at Shepparton in 1999. (Mean ± SE). (Key: □ = unsprayed, ■ = sprayed).

Table 2.3 Actual and potential ranking of the 12 seedlots of *Eucalyptus grandis* and one provenance of *E. saligna* at Shepparton

Provenance	Volume		RGR	
	Actual	Potential	Actual	Potential
Bellthorpe	5	10	6	8
Blackdown	12	11	12	12
Boambee	1	4	3	11
Bruxner Park	4	5	4	5
Bulahdelah	10	1	2	1
Coffs Harbour Seed Orchard	6	2	8	2
Lake Cathie	11	3	11	4
Langleys Road	8	9	5	6
Pine Creek	2	6	7	7
Wahau Trig	7	7	9	10
Wedding Bells	9	8	10	9
Woondum	3	12	1	3

Note: Ranks are based on volume in 1999 and relative growth rate (RGR) from 1993 to 1999. Potential ranks are based on growth of sprayed plants and actual ranks on the growth of unsprayed plants. Ranks range from 1 (best) to 12 (worst).

The differences in ranks between potential and actual volume can be attributed to insect damage although we did not find any relationship between cumulative damage and plant volume (Figure 2.6a; regression testing of cumulative damage on volume in 1999, $P = 0.422$). Relative growth rate, however, did show a significant relationship with damage (Figure 2.6b).

Based on the mean plant volume of sprayed and unsprayed treatments we calculated predicted ranks of plant volume (V_p) for different probabilities (p) of the occurrence of insect damage (Table 2.4). Except at the highest level of probability, the provenance from Coffs Harbour Seed Orchard is predicted to perform the best in terms of plant volume after six years. Even at the highest level of probability of attack it is still predicted to be the second best performing provenance. Provenances from Pine Creek and Bruxner Park are also predicted to do well regardless of the probability of insect attack. For a number of provenances their predicted performance changes markedly as the predicted

level of insect attack changes. The Bulahdelah provenance is predicted to perform well when the chance of insect attack is low, while in contrast provenances such as those from Woondum and Boambee are predicted to grow well when the probability of insect attack is high.

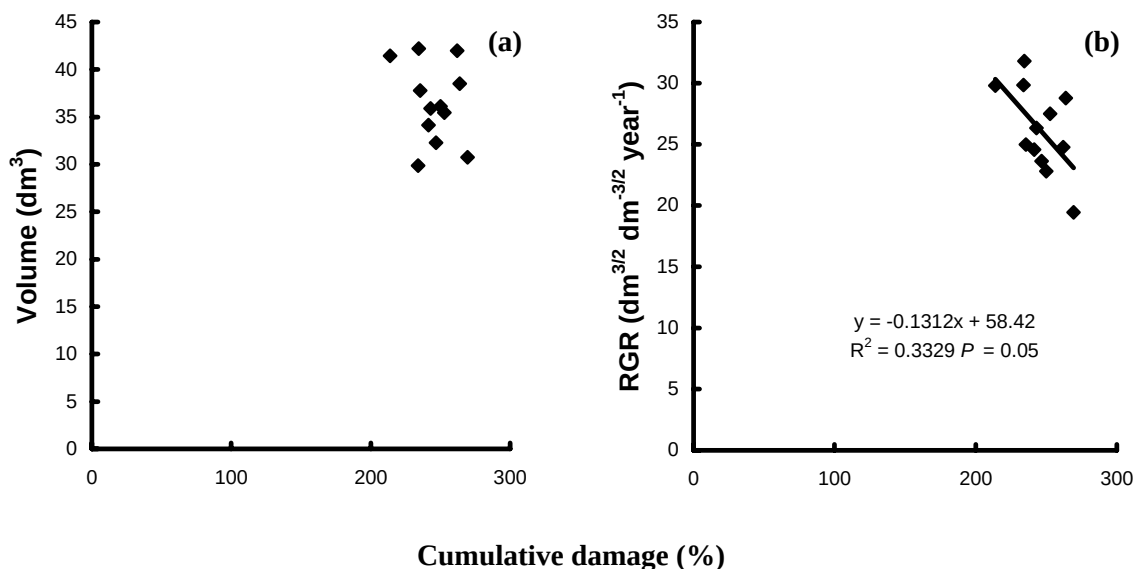


Figure 2.6 Mean cumulative damage against (a) mean volume and (b) RGR for the 12 provenances of *Eucalyptus grandis* at Shepparton in 1999.

Table 2.4 Predicted rank order of the provenances of *Eucalyptus grandis* and *E. saligna* planted at Shepparton for different probabilities of insect attack

Provenance	Probability of attack										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Bellthorpe	9	9	9	9	9	9	8	8	7	7	7
Blackdown	5	5	5	6	8	8	10	11	11	12	11
Boambee	8	8	8	8	6	6	5	3	3	3	3
Bruxner Park	4	4	4	4	4	3	3	4	4	4	4
Bulahdelah	2	2	2	2	2	2	6	7	9	11	12
Coffs Harbour Seed Orchard	1	1	1	1	1	1	1	1	1	1	2
Lake Cathie	6	6	7	7	7	7	7	6	6	6	6
Langleys Road	10	10	10	10	10	10	9	9	8	8	8
Pine Creek	3	3	3	3	3	4	4	5	5	5	5
Wahau Trig	12	12	11	11	11	11	11	10	10	9	9
Wedding Bells	11	11	12	12	12	12	12	12	12	10	10
Woondum	7	7	6	5	5	5	2	2	2	2	1

Note: Ranks are based on the predicted plant volume, $V(p)$

Mildura

Plant volume differed significantly between the two Mildura sites (Figure 2.7a, REML $\Delta dev = 83.63$, $df = 1$, $P < 0.001$). Of the fifteen provenances at Mildura, eight differed significantly between the two sites (Figure 2.7b, REML $\Delta dev = 32.47$, $df = 13$, $P = 0.0021$). Mean plant volume also differed among provenances within each site (Mildura-A: REML $\Delta dev = 66$, $df = 13$, $P < 0.001$; Mildura-B: REML $\Delta dev = 62$, $df = 13$, $P < 0.001$). The best performing provenances at both sites were Pretoria and Loxton selects (Table 2.5). Bruxner Park grew reasonably well at both sites, while several

provenances such as Lake Cathie, Woondum, Pine Creek and Coffs Harbour did better at one site than the other.

Table 2.5 Ranks of provenances at the two Mildura sites based on tree volume in 2000

Provenance	Mildura-A	Mildura-B
Bellthorpe	8	9
Blackdown	13	12
Bruxner Park	5	4
Bulahdelah	14	13
Coffs Harbour SO	7	3
Lake Cathie	3	7
Langleys Road	12	6
Loxton selects	2	2
Mt George	9	8
Orara State Forest	15	15
Pine Creek	11	5
Pretoria	1	1
Wahau Trig	10	11
Wedding Bells	6	10
Woondum	4	14

Cumulative insect damage was negatively correlated with the 2000 mean provenance volume at both sites (Figure 2.8). Insect damage also impacted on survivorship, with plant deaths increasing sharply as cumulative damage levels increased following the autumn gum moth outbreak in 1998 (Figure 2.9). Deaths were mainly restricted to the smaller, weaker plants, rather than the taller healthier plants (Table 2.6).

Mean volume of trees in the sprayed autumn gum moth monitoring sites was greater than mean volume for the same provenance (ERA-2—Loxton selects) at the two trial sites and the unsprayed monitoring sites (Figure 2.10a). However, there was a significant site effect between the sprayed and unsprayed sites in 1998 at the start of the monitoring period ($t = 25.93$, $df = 252$, $P < 0.001$). Spraying occurred in May 1998 and the growth assessments were made in August of that year. Very little growth would have been expected in this period, suggesting that the difference between sprayed and unsprayed modules is a site, rather than a spraying effect. This complicates comparison of plant performance between the sprayed and unsprayed modules in subsequent years. Problems arise determining whether subsequent differences in growth are due to autumn gum moth damage or to the initial site differences being maintained. The growth index RGR corrects for initial plant volume in its calculation and so controls for differences in starting values. We used RGR's to compare performance of sprayed and unsprayed modules over the two growth periods affected by autumn gum moth damage- 1998–1999 and 1999–2000 (Figure 2.10b). There was no significant difference between sprayed and unsprayed sites in the first growth period (1998–1999: $t = 0.88$, $df = 246$, $P = 0.3797$). However, in the second year of the outbreak RGR of unsprayed sites was significantly lower than that of the sprayed sites (1999–2000: $t = 4.1$, $df = 225$, $P < 0.001$).

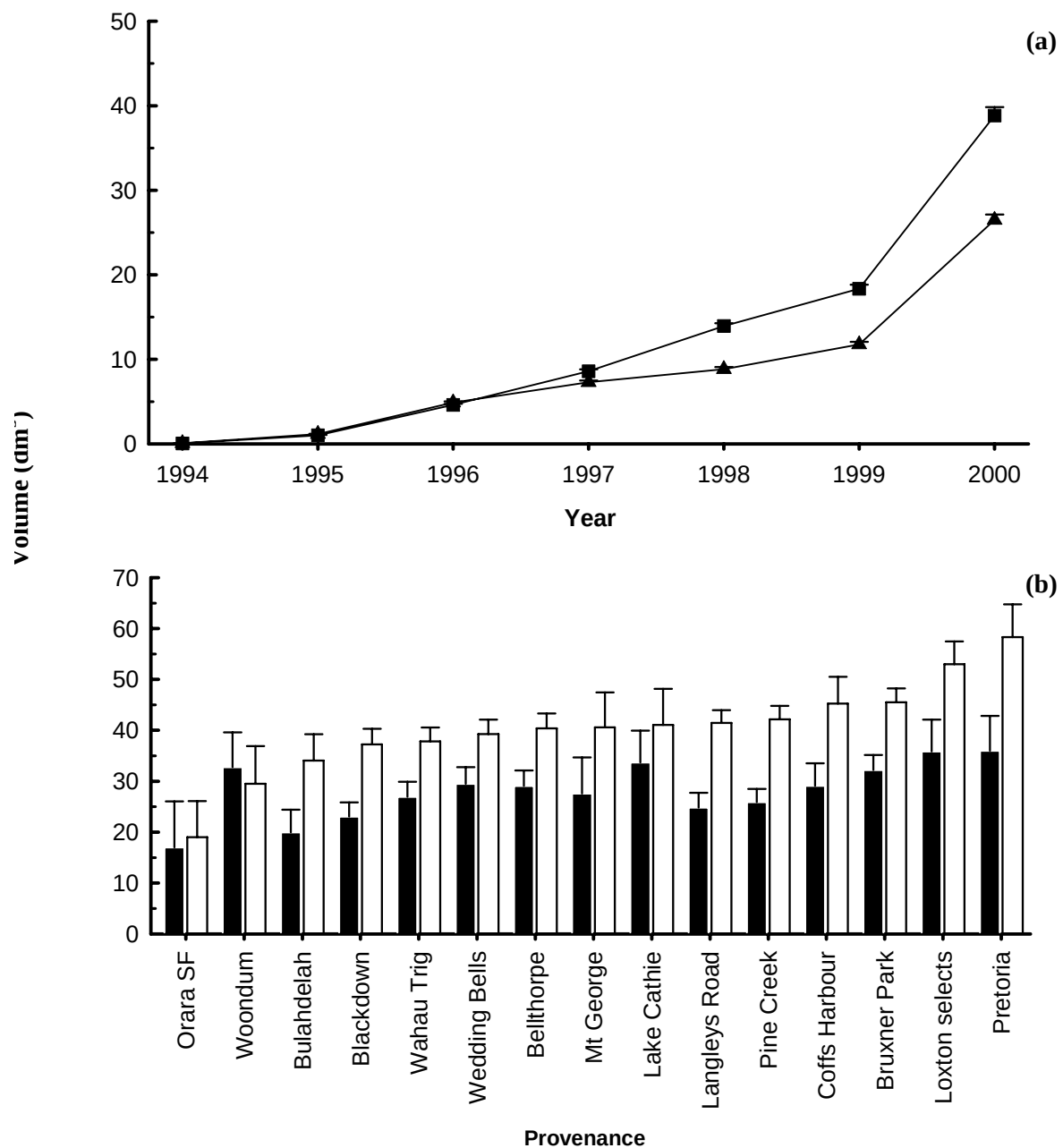


Figure 2.7 Volume (Mean $\pm$ SE) of *Eucalyptus grandis* at Mildura. (a) Growth (volume) at Mildura-A (▲) and Mildura-B (■) and (b) REML estimates of tree volume of the 14 seedlots of *E. grandis* and one provenance of *E. saligna* at Mildura-A (■) and Mildura-B (□) in 2000.

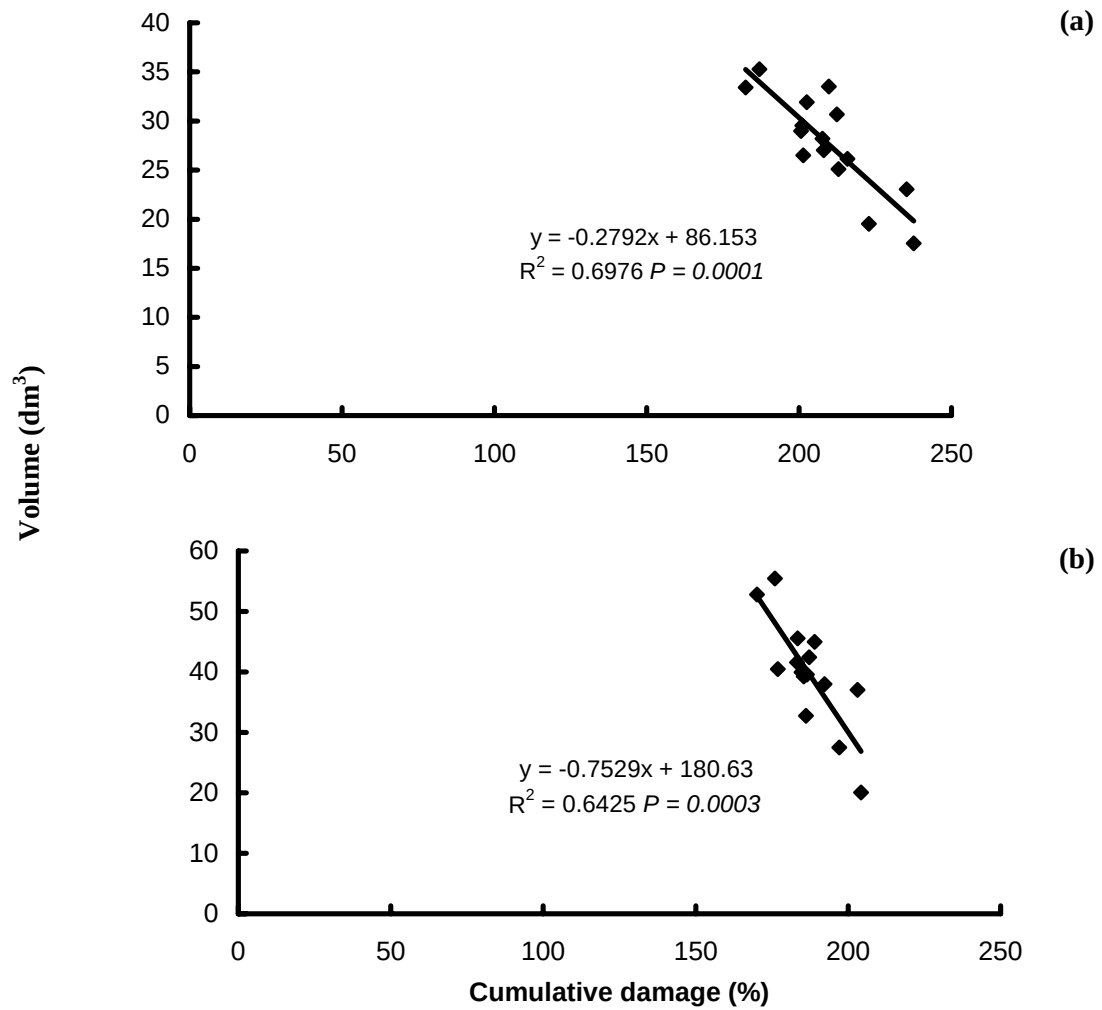


Figure 2.8 Relationship between mean cumulative damage and mean tree volume of provenances of *Eucalyptus grandis* at (a) Mildura-A and (b) Mildura-B in 2000.

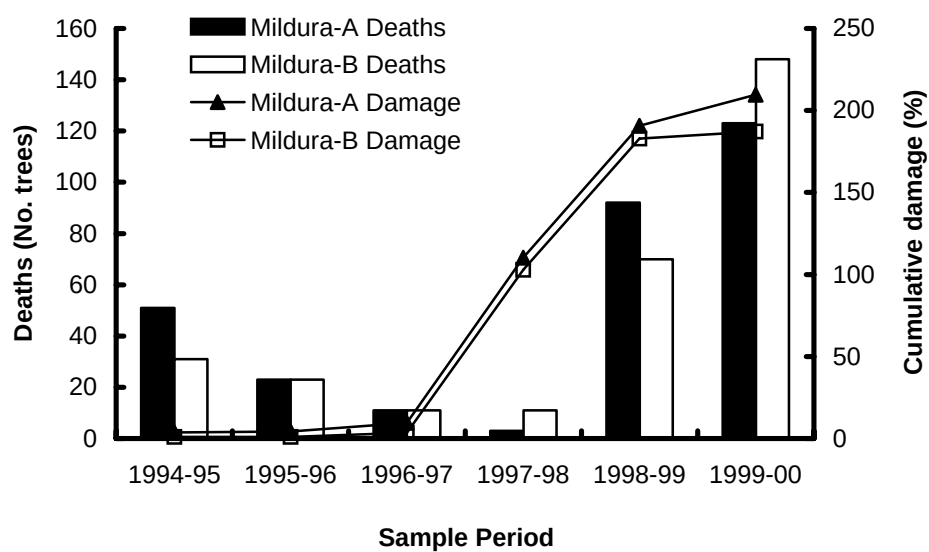


Figure 2.9 Relationship between tree mortality and cumulative damage of *Eucalyptus grandis* at Mildura.

Table 2.6a Change in mortality of trees in different height classes at Mildura-A

1994–95			1995–96			1996–97			1997–98			1998–99			1999–00		
Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead
0–500	35	74.3	0–1000	22	63.6	0–2000	42	9.5	0–2500	36	5.6	0–3000	55	70.9	0–3000	52	100.0
501–1000	106	22.6	1001–2000	92	1.1	2001–4000	174	2.9	2501–5000	176	0.6	3001–6000	227	21.1	3001–6000	110	55.5
1001–1500	153	0.7	2001–3000	186	3.2	4001–6000	436	0.5	5001–7500	422	0.0	6001–9000	491	1.0	6001–9000	247	4.0
1501–3000	610	0.0	3001–8000	651	0.3	6001–11000	282	0.0	7500–13000	288	0.0	9001–14000	142	0.0	9001–18000	503	0.0

Table 2.6b Change in mortality of trees in different height classes over time at Mildura-B

1994–95			1995–96			1996–97			1997–98			1998–99			1999–00		
Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead	Height Range (mm)	No. trees	% dead
0–500	37	75.7	0–1000	21	38.1	0–2000	86	7.0	0–2500	21	33.3	0–3000	28	67.9	0–3000	26	96.2
501–1000	79	3.8	1001–2000	113	8.8	2001–4000	360	0.8	2501–5000	112	1.8	3001–6000	213	18.3	3001–6000	132	57.6
1001–1500	183	0.0	2001–3000	203	2.0	4001–6000	987	0.2	5001–7500	414	0.2	6001–9000	528	1.9	6001–9000	251	17.5
1501–3000	750	0.0	3001–8000	766	0.1	6001–11000	587	0.0	7500–13000	526	0.2	9001–14000	295	0.7	9001–18000	646	0.5

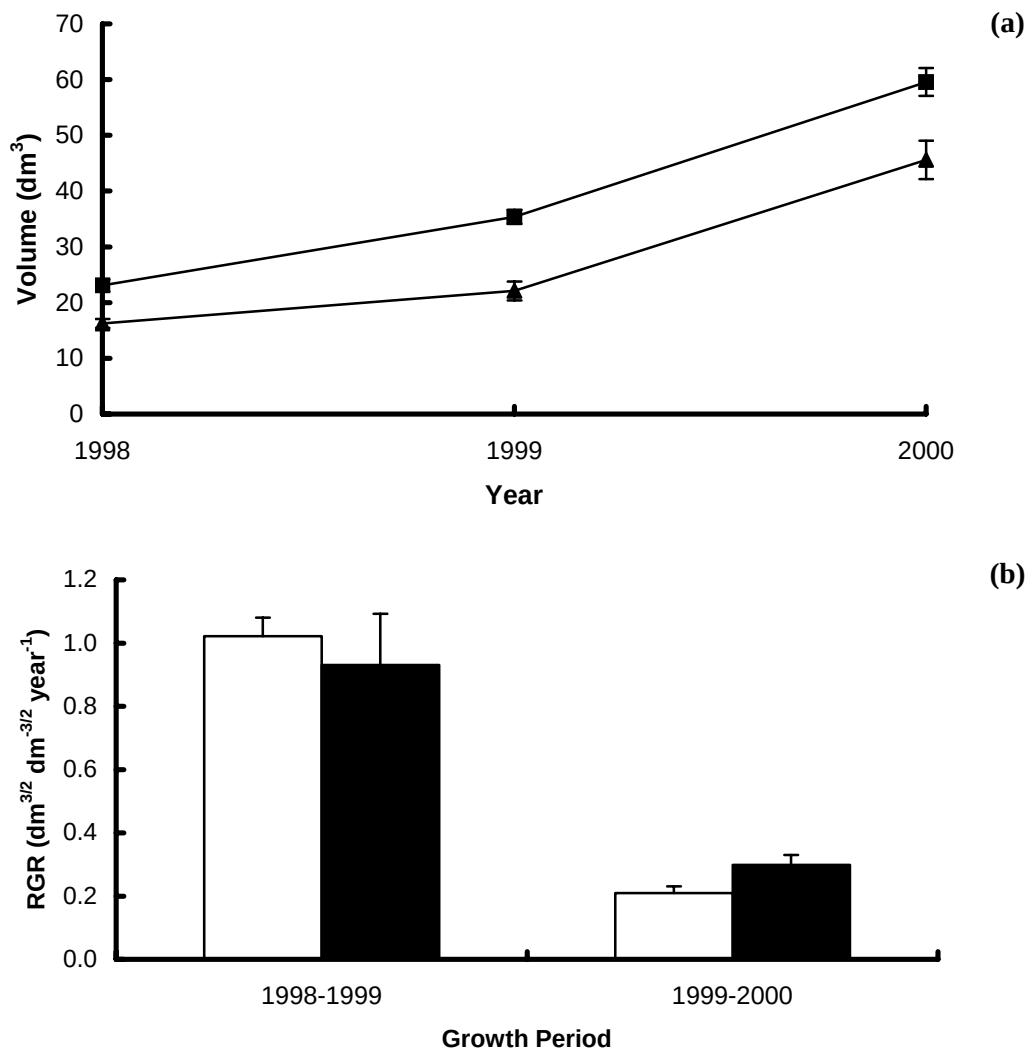


Figure 2.10 Performance of sprayed and unsprayed modules of the *Eucalyptus grandis* Loxton selects (ERA-2) seedlot at Mildura from 1988 to 2000. (a) Volume (Mean $\pm$ SE) of sprayed (■) and unsprayed (▲) modules and (b) RGR (Mean $\pm$ SE) of sprayed (■) and unsprayed (□) modules.

Discussion

Impacts of insect damage aside, growth of *E. grandis* at both Mildura and Shepparton was moderate to poor. At Shepparton the average height increment was 2.4 m per year, while at Mildura it was only 1.4 and 1.5 m per year. Arnold *et. al.* (1996) reported values of 3.4 m per year for irrigated *E. grandis* trials at Loxton, SA where the climate is similar to Mildura. In another effluent irrigated *E. grandis* trial near Wagga Wagga, NSW, the average height of trees reached 9.5 m in less than three years giving an annual height increment of > 3.2 m per year (Myers 1994).

At Mildura this poor growth may have been due to the low daytime humidity typical of the area for much of the growing season. *E. grandis* is a subtropical species and is not well suited to the drier Mediterranean climate of the area. Among the provenances at Mildura the greatest growth was shown by the genetically improved seedlots. Pretoria and Loxton selects were top two seedlots across both sites. The other improved seedlot, Coffs Harbour Seed Orchard, showed good growth at only one of the two sites (Mildura-B). At Shepparton where there were sprayed and unsprayed treatments, the impact of insect damage on plant performance was apparent. Among the sprayed plants and ranking

on volume the best two seedlots were the unimproved natural stand provenance Bulahdelah and the improved seedlot Coffs Harbour. However, among the unsprayed plants the unimproved natural stand provenances, Boambee, Pine Creek and Woondum, performed best and the Coffs Harbour material slipped to a middle rank. When plants were ranked on predicted volume based on the probability of insect attack, the Coffs Harbour material and the Pine Creek and Bruxner Park provenances were predicted to do well regardless of the chance of attack.

That the genetically improved seedlots have the potential to perform well is not surprising. The Loxton selects are the result of intensive mass phenotype selection for genetic improvement, a technique that is very effective in identifying superior parent trees. Other trials of the Coffs Harbour Seed Orchard material in Australia have generally shown its volume growth equal or superior to good natural stand provenances (Cromer *et al.* 1991; Davidson 1993). However, the material also has high inherent genetic variability which may have contributed to its mixed performance. In trials of the seedlot in Sri Lanka some families showed very poor mean volume while others were among the best families in the trial (Bandara *et al.* In press). Somewhat surprising was the relative good performance of the Pretoria material. Trials of seedlots from South Africa have generally shown poor growth relative to natural stand provenances. (Darrow 1983; Rockwell and Meskimen 1991). The original *E. grandis* breeding programs in South Africa began in the late 19th century from material thought to have originated in northern NSW around Orara East. Seedlots from this location have since been shown to have inferior performance (Burgess 1988).

Insect damage at the two sites varied both in its cause and extent. Overall damage levels at Shepparton were moderate with two insect species, autumn gum moth and brown lace lerp, responsible for most of the damage. Mildura suffered one extreme damage event spread over two years. For the first four years mean defoliation per plant at the site was less than 4%. Then in 1998 one species, autumn gum moth, caused total defoliation of the two trial sites, followed by 80% defoliation in 1999. Although the damage profiles at both sites were different, the outcomes were the same. Insect damage decreased plant performance. However, the details of the relationship between damage and plant performance varied between the sites.

At Shepparton although there was a significant difference between the volumes of sprayed and unsprayed plants there was only a 20% difference in the levels of cumulative damage received by the different seedlots. Also there was no relationship at the provenance level between plant volume and cumulative damage of the unsprayed plants. The unsprayed plants, however, did show a negative relationship between provenance RGR and cumulative damage. RGR calculates growth rate correcting for initial plant volume and there were significant differences between the planting volumes of the provenances. This suggests that insect damage had a differential impact on provenance growth, although its effect was not sufficient to overcome the differences in planting volume of the seedlots. In contrast, the range of mean cumulative damage received by the different seedlots at Mildura was also only 20%, but there was a significant negative relationship between cumulative damage and plant volume at both sites.

3 Within species variation in insect damage and growth in *Eucalyptus benthamii*, *E. dorrigoensis*, *E. dunnii*, *E. kartzoffiana* and *Corymbia* spp.

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Summary

We examined (i) the between-species variation and the within and between-provenance variation in susceptibility to insect damage in four eucalypt species (*Eucalyptus benthamii* Maiden & Cabbage *E. dorrigoensis* (Blakely) Johnson & Hill, *E. dunnii* Maiden and *E. kartzoffiana* L. Johnson & Blaxell) and three closely related species of *Corymbia* (*C. maculata* Hook., *C. henryi* Blake and *C. variegata* (Hook.) Hill & Johnson) and (ii) the relationship between insect damage and tree growth. Growth and insect damage of up to 17 native provenances (75–120 families) of each of the species were measured in seed orchards established at two irrigated sites near the township of Deniliquin in the Murray Valley.

Autumn gum moth (*Mnesampela privata* (Guenée)) and leafblister sawfly (*Phylacteophaga* spp.) were the dominant insect herbivores affecting the trees during the trials. Mean annual defoliation at the sites ranged from low for *C. maculata* (0.0%–3.7%) to moderately high for *E. dunnii* (0.3%–67.1%) and *E. benthamii* (1.1%–83.3%). Autumn gum moth was the main cause of damage.

The *Corymbia* species were the most resistant to insect damage. They were also the slowest growing species. *Eucalyptus benthamii* and *E. dunnii* were more susceptible to insect damage. However, these two species showed varying levels of resistance both in the range of damage incurred between provenances and in the level of damage caused by the two dominant herbivores. Seedlots of *E. benthamii* had a greater inherent range of resistance to insect damage than that of *E. dunnii*. However, the overall level of insect damage to *E. benthamii* was higher than that to *E. dunnii*. Leafblister sawfly caused more damage to *E. dunnii* than *E. benthamii*, while autumn gum moth was more damaging to *E. benthamii* than *E. dunnii*. *Eucalyptus benthamii* and *E. dunnii* displayed no cross-resistance to the damage caused by different insect herbivores. Overall growth of both *E. dunnii* and *E. benthamii* was much greater than the *Corymbia* species, although there was large within site variation due to spatial variation. This site variation made determining the impact of insect damage on plant growth difficult, as well as hampering analysis of inter- and intra-seedlot effects.

Introduction

The data presented here examine the relationship between plant growth and susceptibility to insect pests in several species of eucalypts being evaluated for their use in plantation forestry in the Murray-Darling Basin. In common with much of Australia's rural area, the Murray Darling Basin has problems associated with modification to the natural environment by agricultural practices. These include soil erosion, salination, soil acidity, water pollution, rising water tables, weed invasion and the loss of flora and fauna. Wide-scale farm-based tree planting is considered an important component in programs to

reverse this degradation. However, the planting of large areas of farm land to few species of trees raises concerns about pest outbreaks, in particular insect herbivores.

Eucalyptus benthamii Maiden & Cabbage, and the closely related species *E. dorrigoensis* (Blakely) Johnson & Hill and *E. kartzoffiana* L. Johnson & Blaxell, *E. dunnii* Maiden and three closely related *Corymbia* species *C. maculata* Hook., *C. henryi* Blake and *C. variegata* (Hook.) Hill & Johnson have been identified by CSIRO Forestry and Forest Products as having the greatest potential for irrigated farm forestry in the area. Most tree plantings in the area use unimproved seeds, often of unknown provenance. Outcrossed trees of the best provenances have superior survival, faster growth and more desirable form and are therefore more profitable. Research on providing genetically improved stock that optimises returns is needed in the area before large scale tree plantings can go ahead.

A cooperative project was established between landholders in the Deniliquin district of the southern Murray Darling Basin, Treecorp Pty Ltd and CSIRO Forestry and Forest Products in 1995. The project established seed orchards using the species listed above at various sites in the district. The project aimed to combine the functions of superior seed production with provenance-progeny testing and to identify families and provenances that offered the greatest potential for genetic improvement and economic return.

As part of the process of assessing genetic potential, CSIRO Entomology established monitoring protocols to determine what insect threats existed and to measure their impact on plant growth so that any variation in resistance to insect herbivory could be identified. The data reported here presents the results of this work from two of the seed orchards after four years of the project.

Materials and methods

Site description and preparation

The Deniliquin (Riverina district) sites in southern NSW were planted as a seed orchard for a cooperative study between district landholders and CSIRO Forestry and Forest Products to produce genetically improved tree stock for commercial planting programs in the Murray-Darling Basin. The data presented here reports on seed orchards located on private properties at two different sites around the township of Deniliquin. The site at Ken Crossley's property (35° 27' 42.3"S 144° 59' 38.5"E) covers 3.78 hectares and is located 9 km north of Deniliquin. Donald Barclay's property (35° 30' 2.3"S 145° 14' 48"E) is 26 km east of Deniliquin and the seed orchard covered 5.74 hectares. Site preparation consisted of ploughing and ripping. After ripping sites were land formed to create mounds of planting lines approximately 50 cms wide and 25 cms high. Fertiliser was applied to all sites at a rate of 1 bag per hectare of Croplift DAP (NPK plus S) incorporating trelluran as a pre-emergent herbicide treatment for grasses. Tree spacing was 3.2 m between rows and 2.0 m between trees. All sites were planted during the first 3 weeks of November 1995. Post emergent weed controls were also carried out at all sites (simazine for broadleaf species and fusilade for grasses). Sites were irrigated with 30–55 megalitres of water for the first three years.

Tree species

The species used at Deniliquin have very different distributions. *Eucalyptus benthamii*, *E. dorrigoensis*, *E. dunnii* and *E. kartzoffiana* are all very limited in their distributions. The natural range of *E. benthamii* is limited to a 4000 km² area along the Nepean, Wollondilly, Cox and Kedumba River systems west of Sydney (around 33° 49' W, 150° 22' E). Much of this natural stand has been greatly depleted since European settlement through agricultural activities and flooding caused by the Warrangamba Dam (Benson 1985). *Eucalyptus dorrigoensis* and *E. kartzoffiana* are the most closely related species to *E. benthamii* and have even more limited distributions. *Eucalyptus dorrigoensis*

occurs only in the Dorrigo district of the northern tablelands of New South Wales and *E. kartzoffiana* only occurs between Majors Creek and Araluen in south-eastern New South Wales. *Eucalyptus dunnii* is native to a limited area in north-eastern NSW, with smaller areas in adjacent south-east Queensland.

Table 3.1 List of provenance details for each seed orchard at Deniliquin. (SF = State Forest)

Seedlot number	Species	Family composition (No.)	Provenance details				No. of seedlots at each site	
			Location	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	Barclay	Crossley
<i>Eucalyptus benthamii</i> seed orchard								
18751	<i>E. benthamii</i>	individuals	Kedumba Valley (i), NSW	33° 48'	150° 21'	140	1	1
18787	<i>E. benthamii</i>	individuals	Kedumba Valley (ii), NSW	33° 49'	150° 23'	140	29	29
18788	<i>E. benthamii</i>	individuals	Kedumba Valley (iii), NSW	33° 49'	150° 23'	140	12	11
19370	<i>E. benthamii</i>	individuals	Nepean R NNW Camden (i), NSW	34° 02' 34"	150° 41' 40"	80	1	1
19371	<i>E. benthamii</i>	individuals	Nepean R NNW Camden, (ii)NSW	34° 01' 34"	150° 40' 36"	80	2	2
19374	<i>E. benthamii</i>	individuals	Bents Basin, NSW	33° 52' 08"	150° 38' 10"	40	8	8
18763	<i>E. dorrigoensis</i>	individuals	Clouds Ck Armidale, NSW	30° 05'	152° 39'	140	11	9
18360	<i>E. kartzoffiana</i>	individuals	Upper Araluen Valley, NSW	35° 36'	149° 48'	580	10	10
18146	<i>E. grandis</i>	bulk	Coffs Harbour Seed Orchard	-	-	-	1	1
							75 ¹	72
<i>Eucalyptus dunnii</i> seed orchard								
17909	<i>E. dunnii</i>	individuals	Yabbra SF Urben, NSW	28° 35'	152° 29'	550	8	6
17911	<i>E. dunnii</i>	individuals	Spicers Peak SF, QLD	28° 04'	152° 22'	675	7	6
17914	<i>E. dunnii</i>	individuals	Teviot Falls SF, QLD	28° 13'	152° 32'	360	7	-
17915	<i>E. dunnii</i>	individuals	Koreelah SF (i), NSW	28° 16'	152° 28'	625	7	6
17917	<i>E. dunnii</i>	individuals	Koreelah SF (ii), NSW	28° 18'	152° 30'	575	7	6
17920	<i>E. dunnii</i>	individuals	Koreelah SF (iii), NSW	28° 24'	152° 20'	690	7	6
17922	<i>E. dunnii</i>	individuals	Moleton (i), NSW	30° 05'	152° 54'	420	7	6
18263	<i>E. dunnii</i>	individuals	South Yabbra, NSW	28° 35'	152° 29'	580	7	6
18264	<i>E. dunnii</i>	individuals	Yabbra Plains River, NSW	28° 37'	152° 29'	500	7	6
18736	<i>E. dunnii</i>	individuals	Beaury SF, NSW	28° 30'	152° 22'	560	7	6
18737	<i>E. dunnii</i>	individuals	Koreelah SF (iv), NSW	28° 16'	152° 32'	625	7	-
18738	<i>E. dunnii</i>	individuals	Bald Knob SF, NSW	28° 18'	152° 30'	660	7	7
18739	<i>E. dunnii</i>	individuals	Haystack E Sect, NSW	28° 36'	152° 30'	550	7	7
18740	<i>E. dunnii</i>	individuals	Moleton (ii), NSW	30° 09'	152° 53'	500	7	7
18756	<i>E. dunnii</i>	individuals	Acacia Ck, NSW	28° 24'	152° 20'	675	7	7
18757	<i>E. dunnii</i>	individuals	Koreelah SF(v), NSW	28° 16'	152° 32'	625	6	6
18758	<i>E. dunnii</i>	individuals	Moleton (iii), NSW	30° 09'	152° 53'	500	7	7
C86.01	<i>E. grandis</i>	bulk (>24)	Coffs Harbour Seed Orchard	-	-	-	1	1
							120	96
<i>Corymbia maculata</i> seed orchard								
13572	<i>C. henryi</i>	individuals	S. of Grafton, NSW	29° 45'	152° 58'	85	10	10
16899	<i>C. henryi</i>	individuals	Ewingar SF, NSW	29° 01'	152° 29'	520	9	7
13568	<i>C. maculata</i>	individuals	Wyong, NSW	33° 08'	151° 21'	120	5	5
19102	<i>C. maculata</i>	individuals	Bell Rd, Bodalla SF, NSW	36° 11'	150° 06'	124	9	7
19263	<i>C. maculata</i>	individuals	Wingello SF, NSW	34° 44'	150° 11'	580	4	2
19308	<i>C. maculata</i>	individuals	Kiola SF, NSW	35° 35'	150° 20'	70	11	10
19382	<i>C. maculata</i>	individuals	Mottle Range, VIC	37° 37'	148° 13'	280	10	10
19421	<i>C. maculata</i>	individuals	Mumbula, SF, NSW	36° 38'	149° 56'	120	10	9
19422	<i>C. maculata</i>	individuals	Bodalla SF, NSW	36° 11'	150° 06'	60	6	4
19425	<i>C. maculata</i>	individuals	Wingello SF, NSW	34° 45'	150° 11'	550	4	0
13538	<i>C. variegata</i>	bulk (5)	West of Pomona, QLD	26° 22'	152° 40'	150	1	1
16010	<i>C. variegata</i>	individuals	59.4 km NNW Chinchilla, QLD	26° 16'	150° 33'	380	5	5

Seedlot number	Species	Family composition (No.)	Provenance details				No. of seedlots at each site	
			Location	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	Barclay	Crossley
16360	<i>C. variegata</i>	bulk (20)	SW of Warwick, QLD	28° 23'	151° 42'	750	1	1
16757	<i>C. variegata</i>	individuals	Kangaroo SF, NSW	30° 07'	152° 54'	400	9	7
17755	<i>C. variegata</i>	individuals	45 km W of Dalby, QLD	27° 13'	150° 52'	380	5	5
17511	<i>C. variegata</i> ??	bulk (5)	Samford/Mt Glorious, QLD	27° 21'	152° 46'	400	1	1
							100	84

- 1 The layout for the *E. benthamii* seed orchard at Barclay's allowed for 80 families. However, only 75 families were available at the time of planting. Any surplus families in any replicate were used to fill these positions in the design. In this chapter these seedlots are referred to as Fill.

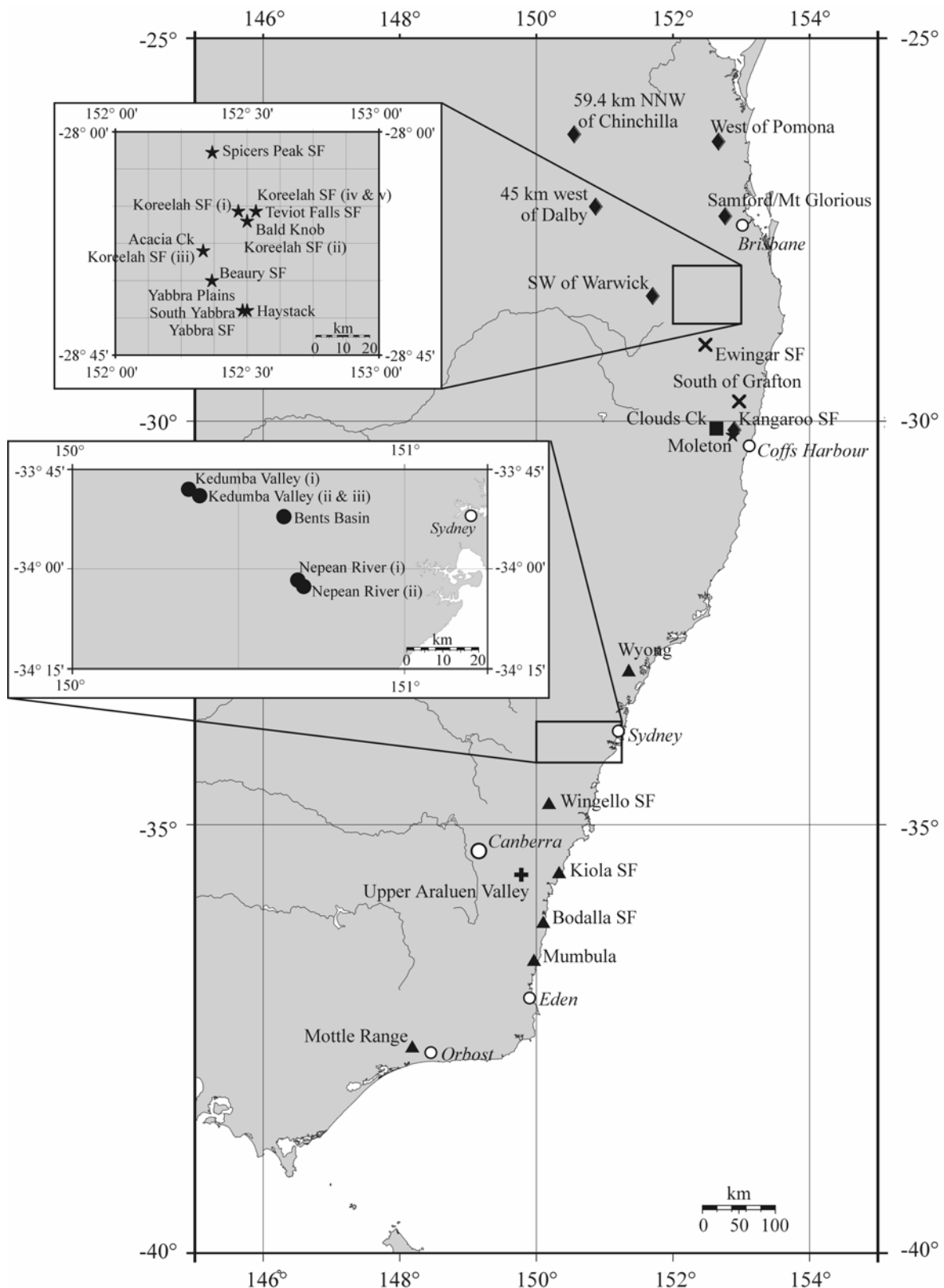


Figure 3.1

Location of natural unimproved provenances and seedlots of *C. henryi* (X), *C. maculata* (▲), *C. variegata* (◆), *E. benthamii* (●), *E. dorrigensis* (■), *E. dunnii* (★) and *E. kartzoffiana* (+) used in this study. Provenance details are given in Table 3.1. Note: Several *E. dunnii* seedlots occurring near Bald Knob were collected from a very small geographical area and are not distinct at the resolution of these maps.

In NSW, natural stands of the species are only found in ten disjunct locations covering about 800 hectares. In contrast *C. maculata* (formally *Eucalyptus maculata*) is a widespread species distributed the south-eastern coast from one isolated pocket north-west of Orbost in Victoria to northern NSW. Closely related to *C. maculata* are *C. henryi* and *C. variegata*. *Corymbia henryi* occurs from Coffs Harbour on the north coast of NSW to Brisbane in Queensland. Pure forms of *C. variegata* occur north of the Macleay River.

The seven species of trees were arranged into three seed orchards at each of the two sites. The *E. benthamii* seed orchard comprised 55 families of *E. benthamii* covering its distinct sources and 11 families of *E. dorrigoensis* and 10 families of *E. kartzoffiana* (Table 3.1 and Figure 3.1). For the *E. dunnii* seed orchard, 120 families covering the species three distinct sources were planted (Table 3.1). The *C. maculata* seed orchard included 100 families made up of 59 families of *C. maculata*, 19 families of *C. henryi* and 22 families of *C. variegata*. Three *C. variegata* seedlots were made up of bulk lots (Table 3.1). In addition to these seedlots, the *E. benthamii* and *E. dunnii* seed orchards each included a seedlot of *E. grandis*. This was done to provide an internal reference against which the performance of the other provenances could be compared.

Site layout

Each of the seed orchards was planted as a randomised complete block design using the experimental design package ALPHA+. Each family was represented in each replicate by a five tree row or line plot, with spacing between rows of 3.2 m and spacing within rows of 2.5 m.

Seed orchard layouts were adjusted to fit the shape of the available land at each site. At Barclay, the *E. benthamii* and *E. dunnii* seed orchards were planted adjacently as two blocks of four reps by four and six rows respectively. There was insufficient room to plant the *Corymbia* seed orchard as one block of equal length rows. Instead it was planted as one block of four replicates by five rows and an adjacent truncated block of one replicate by ten rows. The Crossley site was planted on an L-shaped area of land on the corner of two roads. Along one arm was planted four replicates by twelve rows of *E. benthamii* and a single twelve row replicate of *Corymbia*. The corner of the site was in-filled with a randomised planting of *C. maculata*. The other arm was planted with the remaining three replicates by twelve rows of the *Corymbia* seed orchard and the four replicates by twelve rows of *E. dunnii*. A randomised planting of *E. camaldulensis* separated the *E. dunnii* and *Corymbia* blocks.

Measurements

Plant growth and the level and type of insect damage were regularly measured at all sites (Table 3.2). At all sites an annual measurement of growth and insect damage was made during the winter months when the trees had stopped growing. Depending on the level of activity of herbivorous insects, additional measurements were made as appropriate throughout the year.

Insect damage

The extent of all plant damage, including insect damage, was visually assessed with damage levels for each source recorded separately. To ensure consistency the same observers conducted all damage estimates. Damage levels were scored as percentages on a scale from 0–100% in 10% intervals between 10% and 90% and with finer graduations near 0% and 100% (0%, 1%, 5% and 95%, 99%). Separately assessing damage by different insect species was possible because each insect produced characteristic damage. Where appropriate separate damage assessments were made for different parts of the plant (e.g. foliage, stems) and different stages of development (e.g. immature foliage vs mature foliage). Cumulative damage, the total damage load an individual or seedlot incurred over the trial, was calculated by summing annual percentage damage.

Table 3.2 Sampling schedule at Deniliquin sites (X = sampled, NS = not sampled)

Year	Month	Seed orchard	Barclay		Crossley	
			Damage	Growth	Damage	Growth
1996	Sept	<i>E. benthamii</i>	X	X	X	X
		<i>E. dunnii</i>	X	X	X	X
		<i>Corymbia</i>	NS	NS	NS	NS
1997	May	<i>E. benthamii</i>	X	NS	X	NS
		<i>E. dunnii</i>	X	NS	X	NS
		<i>Corymbia</i>	X	NS	X	NS
	Sept	<i>E. benthamii</i>	X	X	X	X
		<i>E. dunnii</i>	X	X	X	X
		<i>Corymbia</i>	X	X	X	X
1998	April	<i>E. benthamii</i>	X	NS	X	NS
		<i>E. dunnii</i>	X	NS	X	NS
		<i>Corymbia</i>	X	NS	X	NS
	June	<i>E. benthamii</i>	X	NS	X	NS
		<i>Corymbia</i>	NS	NS	X	NS
	July	<i>Corymbia</i>	NS	X	NS	NS
	Aug	<i>E. benthamii</i>	NS	NS	NS	NS
	Sept	<i>E. benthamii</i>	NS	X	X	NS
		<i>E. dunnii</i>	X	X	X	X
		<i>Corymbia</i>	X	NS	X	NS
1999	June	<i>E. benthamii</i>	X	NS	X	NS
		<i>E. dunnii</i>	X	NS	X	NS
		<i>Corymbia</i>	X	NS	X	X
	Sept	<i>E. benthamii</i>	X	X	X	X
		<i>E. dunnii</i>	X	X	X	X

Plant growth

The height and diameter of each plant were used as measures of plant growth. Initially tree height was measured to the nearest 0.1 m using graduated height poles. As the plantations developed this became impractical and the poles were replaced with an electronic measuring device (VERTEX). The standard measure of tree girth was diameter at breast height (DBH) which is defined as the diameter at 1.3 m above ground level. However, this was only practical when trees were at least 2–2.5 m tall. As we were interested in detecting long term impacts of insect damage on young trees it was necessary to measure tree diameter at least annually from the time the trees were planted. When trees were too small for DBH measurements, diameter at ground level (DGL) was used as an alternative. Individual tree volume (V in dm^3) was calculated using the conical volume equation:

$$V = \frac{(DBH / 2)^2 \times Ht \times \pi}{3 \times 100^3}$$

where Ht = height in mm and DBH is diameter at breast height in mm. Only a subset of trees was included in the volume calculations. Trees with multiple trunks or trees that had suffered substantial trunk or crown damage were excluded, as the conical equation is not a good estimator of volume for these trees. Furthermore, in commercial plantations these trees would normally be thinned as part of routine maintenance.

Analysis

During the course of the trials at Deniliquin, it became apparent that there was a large amount of spatial variation within the Crossley and Barclay sites. At Barclay the soil type varied dramatically across the site and affected growth rates. At Crossley, mishaps during laser levelling resulted in different soil conditions across the site with some areas losing all topsoil as they were scraped back to the clay subsoil. Growth rates were correspondingly uneven with trees growing in the areas with little topsoil being noticeably smaller than those planted in areas with normal soil conditions. The extent of the differences in growth rates at Barclay and Crossley was so great as to present a problem for analysis. The magnitude of the spatial effect was too large for REML to accommodate. Instead, we partitioned plants into size groups based on height in 1998 and analysed each size group separately. Within each size group, cumulative damage and tree volumes were calculated for each provenance or seedlot. Regression was used to test for any relationship between cumulative damage and growth. Groups were based on the 1998 growth data because CSIRO Forest and Forest Products, as part of their management of the trials, began selective thinning of the sites in 1999. The winter assessment of 1998 was the last where the full complement of trees was present. All statistical analyses were performed using Genstat (Genstat 5 Committee 1993).

Results

Insect damage

Over the period of the trial all sites species experienced some damage (Table 3.3). The *Corymbia* seed orchards had the lowest level of damage. The highest level of damage to a *Corymbia* seed orchard was at Barclay in June 1999 with a mean defoliation of only 3.7%. On several occasions the *Corymbia* seed orchards at both Barclay and Crossley incurred no damage (Table 3.3). Damage levels to *E. benthamii* and *E. dunnii* seed orchards were much higher with mean annual defoliation up to 83.3% and 67.1% respectively.

While there was a variety of insect species attacking the trees at Deniliquin, the major cause of insect damage was leafblister sawfly and autumn gum moth (Table 3.4). Leafblister sawfly damage was the major source of insect damage between May 1997 and April 1998 (Table 3.4), although by April 1998 damage levels were low (Table 3.3). From 1998 onwards autumn gum moth numbers increased at both Crossley and Barclay and a corresponding increase in damage occurred. Autumn gum moth damage reached its highest level in the winter of 1999 (Tables 3.3 and 3.4).

The impact of leafblister sawfly and autumn gum moth damage was not uniform across all seed orchards or all sites (Tables 3.5 and 3.6). Leafblister sawfly caused higher levels of damage to the *E. dunnii* seed orchards than to the *E. benthamii* seed orchards and the seed orchards at Barclay received more damage than those at Crossley (Table 3.5). Damage to the *Corymbia* seed orchards was minimal at both sites.

Initially autumn gum moth damage was greater at Barclay (Table 3.6), but by September 1999 the highest damage was at Crossley. The *E. benthamii* trials suffered the greatest cumulative level of damage. There was, however, considerable variation in the levels of damage received by the different species in the *E. benthamii* seed orchard. For example in September 1998 the mean percentage defoliation at Barclay was $41.8 \pm 33.6\%$ (0%–100%) for *E. benthamii*, $27.8 \pm 36.0\%$ (0%–100%) for *E. dorrigoensis* and $85.5 \pm 24.6\%$ (0%–100%) for *E. kartzoffiana*. In September 1999 the values were $44.5 \pm 33.3\%$ (0%–100%), $85.7 \pm 26.6\%$ (10%–100%) and $83.1 \pm 21.7\%$ (10%–100%) respectively. Autumn gum moth damage to *C. maculata* was insubstantial and is not included in Table 3.6.

Table 3.3 Mean percentage insect damage per tree for each site and seed orchard at Deniliquin, 1996–1999. Mean $\pm$ SE (range).

Site	Sample	Seed orchard			
		<i>E. benthamii</i>	<i>E. dunnii</i>	<i>Corymbia</i>	
Barclay	Sept 1996	1.1 $\pm$ 0.20 (0–100)	0.3 $\pm$ 0.06 (0–70)	-	
	May 1997	11.8 $\pm$ 0.39 (0–80)	26.2 $\pm$ 0.41 (0–80)	2.9 $\pm$ 0.13	(0–30)
	Sept 1997	29.8 $\pm$ 0.62 (0–100)	26.2 $\pm$ 0.41 (0–80)	3.3 $\pm$ 0.27	(0–50)
	April 1998	1.1 $\pm$ 0.13 (0–30)	0.03 $\pm$ 0.02 (0–5)	1.1 $\pm$ 0.13	(0–15)
	Sept 1998	44.8 $\pm$ 0.98 (0–100)	10.6 $\pm$ 0.40 (0–100)	0.0	
	June 1999	53.6 $\pm$ 1.13 (0–100)	46.7 $\pm$ 0.91 (0–100)	3.7 $\pm$ 0.53	(0–100)
	Sept 1999	54.2 $\pm$ 1.18 (0–100)	47.3 $\pm$ 0.96 (0–100)	0.0	
Crossley	Sept 1996	5.3 $\pm$ 0.47 (0–100)	0.8 $\pm$ 0.13 (0–95)	-	
	May 1997	3.8 $\pm$ 0.28 (0–100)	14.1 $\pm$ 0.26 (0–75)	2.6 $\pm$ 0.17	(0–40)
	Sept 1997	9.2 $\pm$ 0.51 (0–100)	22.4 $\pm$ 0.44 (0–100)	3.3 $\pm$ 0.30	(0–70)
	April 1998	0.1 $\pm$ 0.03 (0–5)	0.7 $\pm$ 0.07 (0–20)	0.1 $\pm$ 0.03	(0–5)
	Sept 1998	19.4 $\pm$ 1.02 (0–100)	3.1 $\pm$ 0.14 (0–100)	0.0	
	June 1999	27.2 $\pm$ 1.18 (0–100)	30.6 $\pm$ 0.85 (0–100)	0.0	
	Sept 1999	83.3 $\pm$ 1.03 (0–100)	67.1 $\pm$ 1.00 (0–100)	0.0	

Table 3.4 Relative proportion (%) of damage caused by each insect species recorded at Deniliquin

Cause of damage	Sept 1996	May 1997	Sept 1997	Apr 1998	Sept 1998	Jun 1999	Sept 1999
Autumn gum moth	92.2%	0.3%	9.3%		90.6%	100%	99.9%
Galls	< 0.1%						
Gumleaf skeletonizer			< 0.1%				
Leaf tier	6.0%		0.2%	0.6%			
Leafblister sawfly	0.3%	99.6%	90.1%	99.4%	9.2%		
Leaf beetles		< 0.1%		< 0.1%			
Pergid sawflies	1.0%	0.1%	0.1%		0.2%		0.1%
Scale	0.4%		0.1%		< 0.1%		
Unknown chewers			0.3%				

Table 3.5 Leafblister sawfly damage at Deniliquin in 1997

Sample	Seed orchard	Site	
		Barclay	Crossley
May 1997	<i>E. benthamii</i>	11.7%	3.6%
	<i>E. dunnii</i>	26.3%	14.0%
	<i>C. maculata</i>	2.9%	2.6%
Sept 1997	<i>E. benthamii</i>	23.2%	1.7%
	<i>E. dunnii</i>	44.7%	12.8%
	<i>C. maculata</i>	3.3%	3.2%

Table 3.6 Autumn gum moth damage at Deniliquin in 1998–99

Sample	Seed orchard	Site	
		Barclay	Crossley
Sept 1998	<i>E. benthamii</i>	44.6%	19.5%
	<i>E. dunnii</i>	10.6%	3.1%
June 1999	<i>E. benthamii</i>	53.8%	27.6%
	<i>E. dunnii</i>	46.9%	30.9%
Sept 1999	<i>E. benthamii</i>	54.2%	83.7%
	<i>E. dunnii</i>	47.5%	67.4%

Cumulative damage varied both between sites and among seedlots in seed orchards (Figure 3.2). Variation was greatest among the *E. benthamii* provenances, partly due to the greater susceptibility of the *E. kartzoffiana*. However, the range of damage levels was still only moderate. At Barclay mean cumulative damage ranged from $109.1 \pm 10.8\%$ to $162.5 \pm 4.7\%$, while at Crossley the values were $85.7 \pm 6.0\%$ and $156.8 \pm 5.0\%$ respectively. Except for trees from the Kedumba Valley (ii) seedlot where damage was the same at both sites, provenance cumulative damage levels were higher at Barclay than at Crossley (Figure 3.2a). Cumulative damage to the *E. grandis* reference seedlot at Barclay was greater than that to all the other provenances in the seed orchard, while at Crossley the *E. grandis* reference seedlots incurred the lowest level of cumulative damage of all the provenances. Relative levels of insect resistance among provenances were similar across sites. Bents Basin and Nepean River (ii) were the most resistance seedlots at both sites while *E. kartzoffiana* provenance, Upper Araluen Valley, was the most susceptible. There was little variation between provenances in cumulative damage levels for the *E. dunnii* seed orchard (Figure 3.2b). Values range from $100.1 \pm 5.7\%$ for the most resistant provenances and $122.4 \pm 5.3\%$ for the most susceptible provenance at Barclay, while at Crossley the values were $87.5 \pm 4.6\%$ and $106.5 \pm 3.4\%$ respectively. Provenance cumulative damage levels were either similar at both sites, or slightly higher at Barclay (Figure 3.2b). At both sites the *E. grandis* reference seedlot was the most resistant provenance in the *E. dunnii* seed orchard.

Variation in provenance damage levels by the two main insect herbivores, autumn gum moth and leafblister sawfly, was very similar to the patterns seen in total mean cumulative damage (Figures 3.3 and 3.4). Variation in susceptibility among provenances was greatest in the *E. benthamii* seed orchards. The trees most susceptible to autumn gum moth in the *E. benthamii* seed orchard were those from the *E. kartzoffiana* provenance Upper Araluen Valley. Trees from this provenance incurred approximately 2–3 times the cumulative damage of trees from the most resistant provenance Bents Basin (Figures 3.3a and 3.3c).

While cumulative autumn gum moth damage was greater at Barclay than Crossley, trees from the Upper Araluen Valley provenance incurred similarly high levels of damage at both sites. Trees from the Upper Araluen Valley provenance incurred proportionally higher damage than trees in other provenances in the *E. benthamii* seed orchard when moth numbers were low. For example in 1997 mean autumn gum moth damage to trees from the Upper Araluen Valley provenance was 3.9% (1.1%–6.5%). In contrast, when moth numbers at Barclay increased in 1999, mean autumn gum moth damage to the Upper Araluen Valley provenance was 48% while mean autumn gum moth damage to the remainder of the provenances in the seed orchard was 34.2% (24.3–47.1%). There was only moderate variation in cumulative autumn gum moth damage incurred by the other provenances in the *E. benthamii* seed orchards (Figures 3.3a and 3.3c). Other than the Upper Araluen Valley provenance, trees from the Kedumba Valley seedlots tended to be the most susceptible to autumn gum moth attack, while trees from the Bents Basin provenance were the most resistant. At both sites the *E. grandis* reference seedlot had the lowest level of autumn gum moth attack. Variation in autumn gum moth damage among provenances in the *E. dunnii* seed orchards was low (Figures 3.3b and 3.3d). Cumulative damage levels ranged from 33.2% to 49.3% at Barclay and from 40.6% to 58.1% at Crossley. The relative resistance of provenances also varied between sites. Trees from the Koreelah SF

provenances were among the most susceptible at both sites, but the provenance with the most resistant trees varied between sites (Figures 3.3b and 3.3d). Among the provenances in the *E. dunnii* seed orchards at both sites, the *E. grandis* reference seedlot had the lowest level of cumulative autumn gum moth damage.

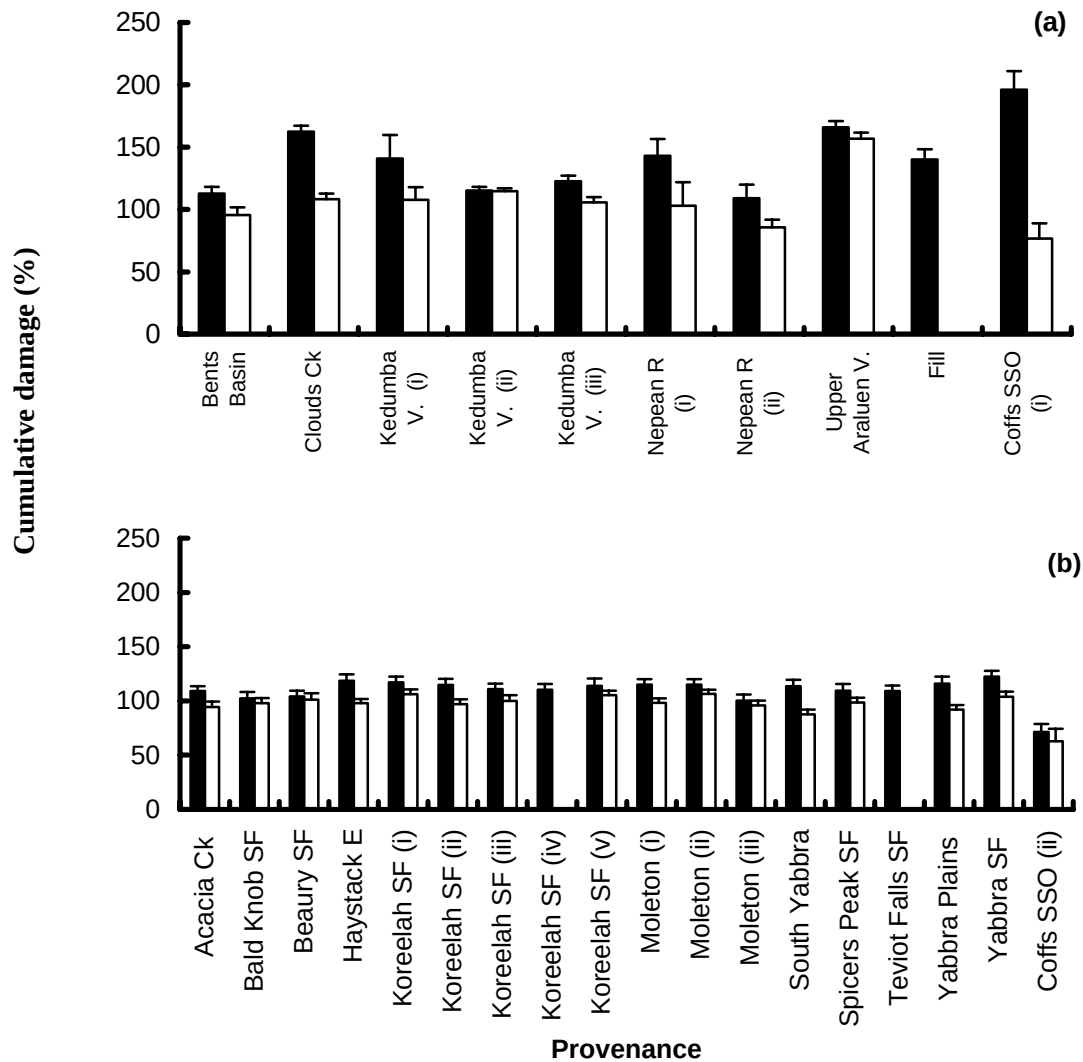


Figure 3.2 Mean cumulative damage among provenances of (a) *E. benthamii* seed orchard and (b) *E. dunnii* seed orchard at Barclay (■) and Crossley (□). Coffs Harbour SSO are the *E. grandis* reference seedlots.

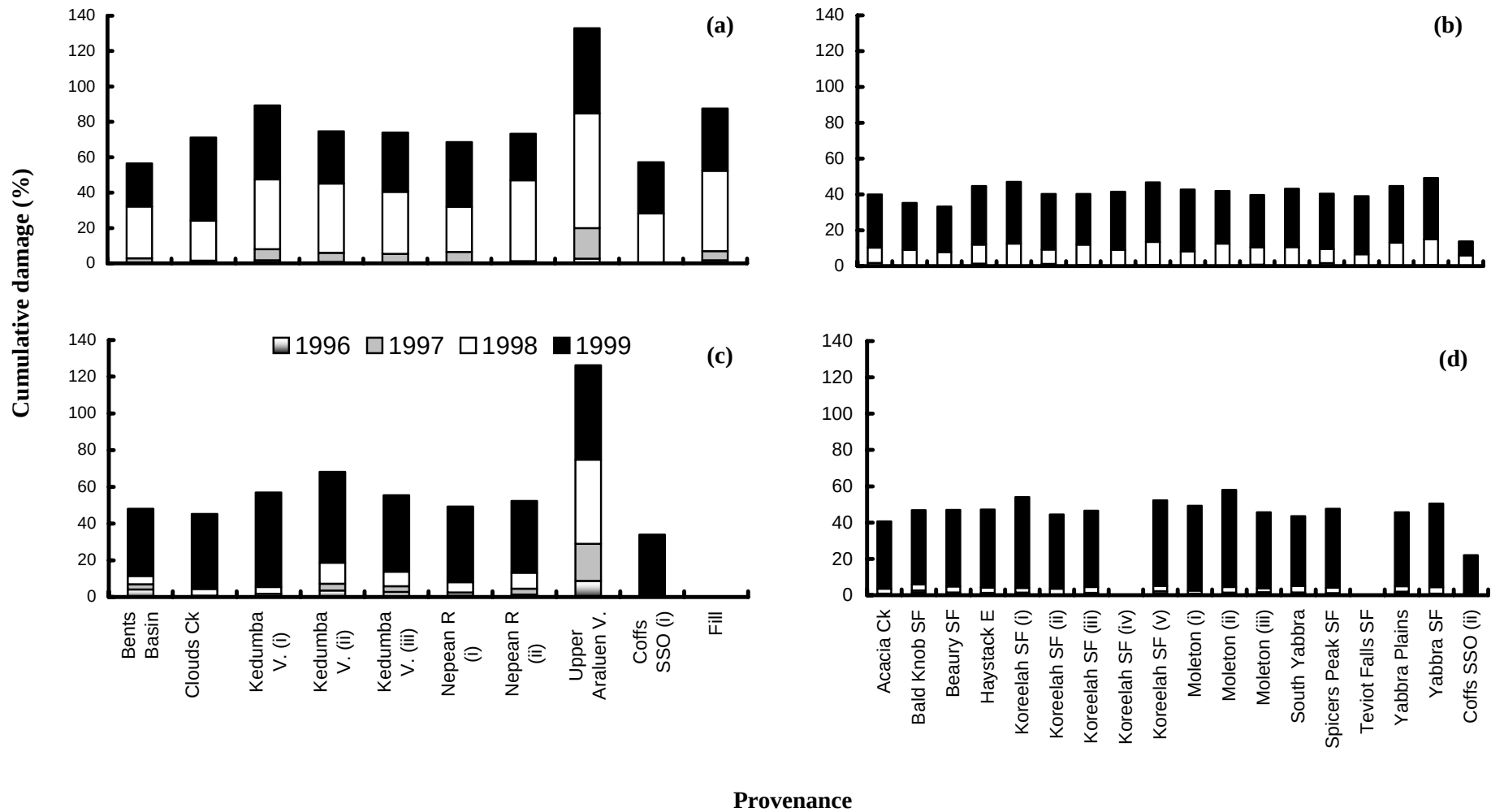


Figure 3.3 Mean annual damage to provenances by autumn gum moth. (a) *E. benthamii* and (b) *E. dunzii* seed orchards at Barclay, (c) *E. benthamii* and (d) *E. dunzii* seed orchards at Crossley. The *E. grandis* reference seedlots are Coffs Harbour SSO.

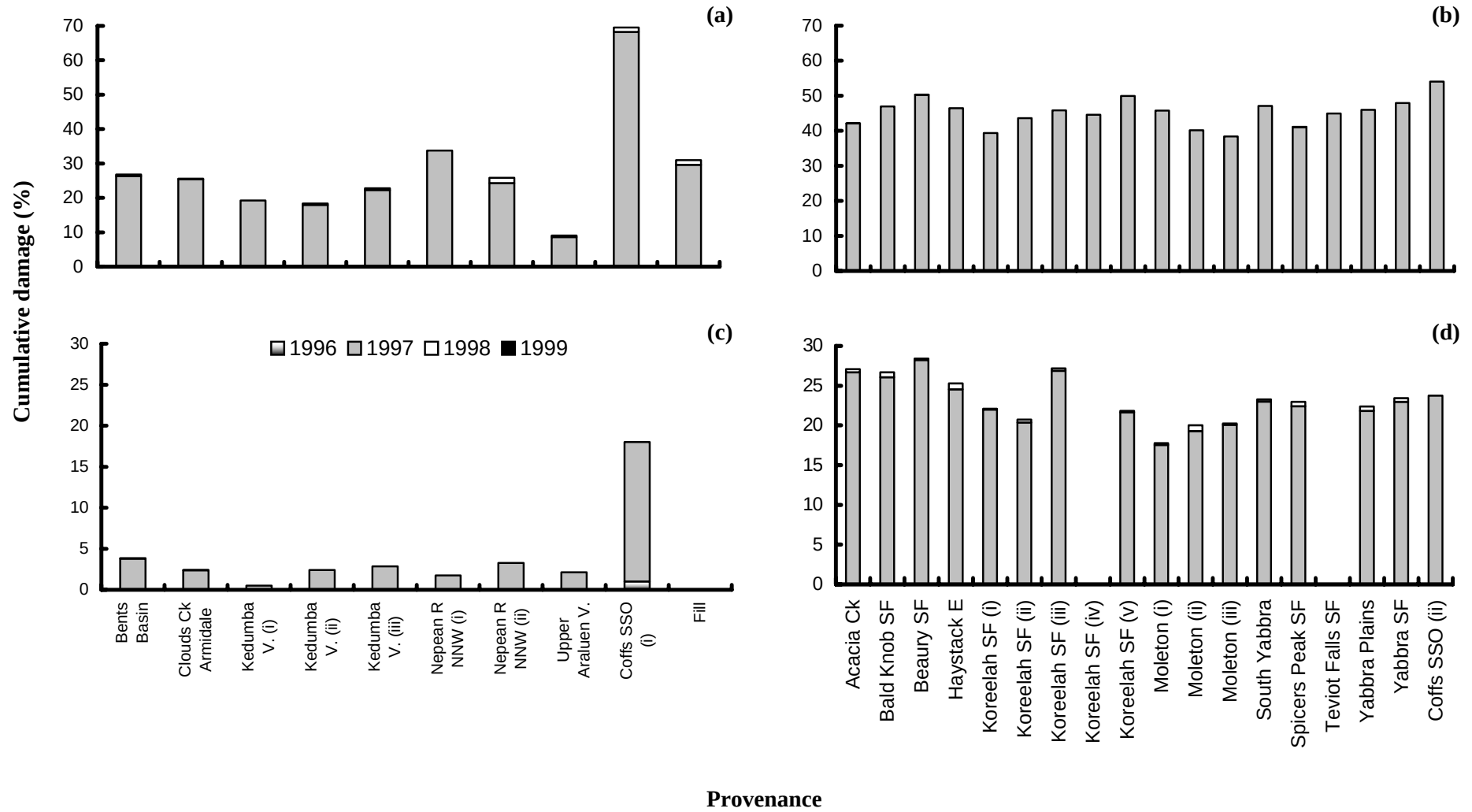


Figure 3.4 Mean annual damage to seedlots by leafblister sawfly. (a) *E. benthamii* and (b) *E. dunnii* seed orchards at Barclay (c) *E. benthamii* and (d) *E. dunnii* seed orchards at Crossley. The *E. grandis* reference seedlots are Coffs Harbour SSO.

Provenances in the *E. benthamii* seed orchards incurred only low levels of leafblister sawfly damage (Figures 3.4a and 3.4c) and there was correspondingly little between provenance variation in damage. At Barclay, where damage levels were highest, trees from the Upper Araluen Valley provenances were the most resistant to leafblister sawfly while trees from the Nepean River (i) provenance were the most susceptible (Figure 3.4a). Trees from the *E. grandis* reference seedlot incurred much higher levels of damage than any other provenances in the *E. benthamii* seed orchards at either site. Provenances in the *E. dunnii* seed orchard incurred higher levels of leafblister sawfly damage than provenances in the *E. benthamii* seed orchard. There was, however, little variation between provenance in damage levels for the *E. dunnii* seed orchard (Figure 3.4b, 3.4d). At Barclay where cumulative damage levels were approximately double that at Crossley, the most resistant provenance was Moleton (iii) while the most susceptible was Beaury SF. However, the relative resistances of provenances varied between sites with no provenance or groups of provenances showing consistently high or low resistant at both sites. Cumulative leafblister sawfly damages levels to *E. dunnii* provenances were similar to that of the *E. grandis* reference seedlots at both sites (Figures 3.4b, 3.4d).

Eucalyptus benthamii showed no cross resistance to leafblister sawfly and autumn gum moth either at the species or provenance level. For example the *E. kartzoffiana* provenance, Upper Araluen Valley, while the most resistant to leafblister sawfly, was the most susceptible provenance to autumn gum moth (compare Figures 3.3 and 3.4). Variation in damage levels between *E. dunnii* provenances was too slight for cross-resistance to be considered.

Plant growth

Tree size varied considerable between the two sites and between seed orchards within sites, although the mean tree volume of the *E. benthamii* and *E. dunnii* seed orchards at Barclay and the *E. dunnii* seed orchard at Crossley were similar (Table 3.7). Trees in the *Corymbia* seed orchards had the smallest volumes at both sites, while the *E. benthamii* seed orchard at Crossley had poor growth. Unfortunately much of the variation in growth was due to site effects rather than inherent differences between the seedlots in each seed orchard. The soil conditions at both Barclay and Crossley changed markedly across the sites and the differences in tree heights can be related to these changes (data not shown).

To control for the confounding effect of within site spatial variation, height distributions in 1998 (Figure 3.5) were used to allocate individual trees into two height classes for each combination of site and seed orchard (Table 3.8). These height class correspond approximately to slowly growing trees in the poorer soils (class 1) and faster growing trees in better soils (class 2). The trees in these height classes were then used to test for any relationship between insect damage levels and tree growth. The height data from 1998 were used to allocate trees into classes as it was the last measurement that included all trees before selective thinning operations started in 1999. Thinning was not done randomly, so the trees remaining after thinning were not an unbiased sample.

Table 3.7 Tree volumes (dm³) at Barclay and Crossley for each seed orchard in 1998. (Mean $\pm$ SE (Range))

Seed orchard	Barclay		Crossley	
<i>E. benthamii</i>	9.89+0.352	(0.0004–87.0)	2.97+0.100	(0.0002–20.5)
<i>E. dunnii</i>	9.07+0.222	(0.0039–50.1)	10.29+0.238	(0.0047–51.6)
<i>Corymbia</i>	6.80+0.172	(0.0004–46.1)	1.53+0.039	(0.0001–9.7)

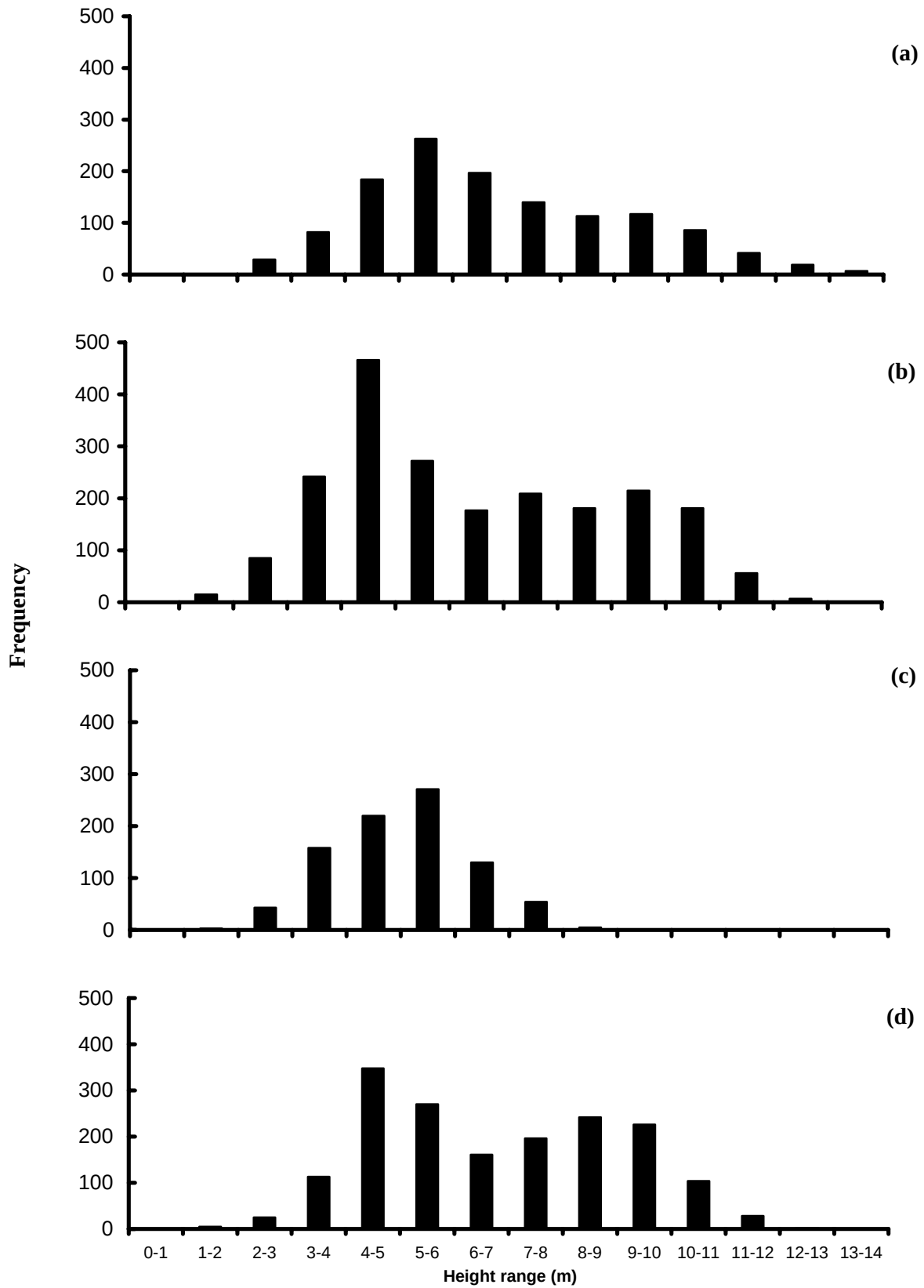


Figure 3.5 Plant height distributions in 1998 for (a) *E. benthamii* and (b) *E. dunnii* at Barclay and for (c) *E. benthamii* and (d) *E. dunnii* at Crossley.

Table 3.8 Size classes (m) used to analyses provenance responses to insect damage differences at Barclay and Crossley.

Height Class	Seed orchard			
	Barclay		Crossley	
	<i>E. benthamii</i>	<i>E. dunnii</i>	<i>E. benthamii</i>	<i>E. dunnii</i>
1	≤ 6.48	≤ 5.40	≤ 3.49	≤ 5.40
2	≥ 6.50	≥ 5.50	≥ 3.50	≥ 5.50

Mean tree volume for class 2 provenances in 1999 varied two to seven fold between the two sites and seed orchards (Figure 3.6), although much of this variation was due to the poor growth of the *E. benthamii* seed orchard at Crossley. Between provenance variation was greatest in the *E. benthamii* seed orchard at Barclay, where there was a three fold difference in volume between trees in the smallest and largest provenance (Figure 3.6a). However, there was little variation in volume between the other provenances in the seed orchard. At Crossley where growth of the *E. benthamii* seed orchard was very poor, the range in size from the smallest to the largest provenance was 6.77 dm³ to 11.94 dm³ respectively. Growth of the *E. grandis* reference seedlot was relatively poor compared to other provenances at both *E. benthamii* seed orchards. There was little variation in the range of volumes among the *E. dunnii* seed orchards provenances, both within and between sites (Figure 3.6b). At Barclay the range of values was 32.6 dm³ to 51.2 dm³, while at Crossley it was 35.7 dm³ to 52.1 dm³. The relative performance of the *E. grandis* reference seedlot with respect to the *E. dunnii* provenances varied between the two sites (Figure 3.6b).

Using ranks based on the relative performance of class 2 trees across the two sites, the best of the *E. benthamii* trees were the three seedlots from the Kedumba Valley provenance (Table 3.9). Trees from the Nepean River (i) seedlot had the highest volume at Crossley, but at Barclay no individuals grew tall enough to be included among the class 2 trees. In contrast trees from the Nepean River (ii) seedlot ranked best in terms of growth at Barclay, but their overall ranking was brought down by poor growth at Crossley. The Upper Araluen Valley provenance ranked consistently poorly across all the sites and the height classes. Three *E. dunnii* seedlots (Acacia Ck., Haystack and the Koreelah SF (v) seedlot) ranked consistently well by volume across the two sites (Table 3.9). A few provenances, such as Beaury SF and Koreelah SF (iii) ranked well by volume at one site, but poorly at the other. However, given the small differences in volume between the *E. dunnii* provenances such changes in ranking are relatively unimportant.

There was no significant relationship between insect damage and seedlot growth in 1998 (Figure 3.7), while in 1999 the only significant correlation between growth and damage was for the class 2 *E. dunnii* provenances at Barclay (Figure 3.8). These relationships between damage and growth were not strong, the regression explaining only 40% of the variance (Figure 3.8f).

Discussion

It is widely accepted that competition for limited resources leads to trade offs between plant growth and the mechanisms of plant resistance to herbivores (Bazzaz *et al.* 1987; Chapin *et al.* 1990). Faster growing plants (species, populations or individuals) are thought to be more susceptible to herbivores than slower growing plants (species, populations or individuals). The results of such trade-offs can be seen in the growth rates observed in this study. *Corymbia maculata* and its related species *C. henryi* and *C. variegata* are known to be highly resistant to insect attack (Stone *et al.* 1998) and in this study they had low levels of insect attack. Annual mean defoliation in the *Corymbia* seed orchards never exceeded 4% and on only two occasions did damage to individual trees equal or exceed 40%. The *E. benthamii* and *E. dunnii* seed orchards were more heavily attacked by insects with seedlots in each orchard showing a range of susceptibility to insect attack. Allowing for the large effects of within site spatial variation on plant growth, the *Corymbia* seed orchards had the slowest growth rates in the trial.

Both the *E. benthamii* and *Corymbia* seed orchards at Crossley were affected by reduction in top soil levels due to faulty laser levelling during site preparation. The extent of this effect graduated across the site with the largest impact being in the block where the *E. benthamii* seed orchard was planted. Even so at this site the *E. benthamii* seed orchard out grew the *Corymbia* seed orchard.

No clear evidence was found for cross-resistance to leafblister sawfly and autumn gum moth, the two dominant insect herbivores in the study. Previous plantation experiments have shown such a relationship between species and *E. globulus* Labill. (Farrow *et al.* 1994), although evidence of cross-resistance was not found between Christmas beetles (*Anoplognathus* spp.) and other *E. globulus* insect herbivores (see Chapters 4 and 5). However, the cumulative levels of insect damage reported here are not high and may be below the threshold where cross-resistance is evident. Certainly the levels or duration of damage were much higher where cross-resistance has been reported for *E. globulus* plantations.

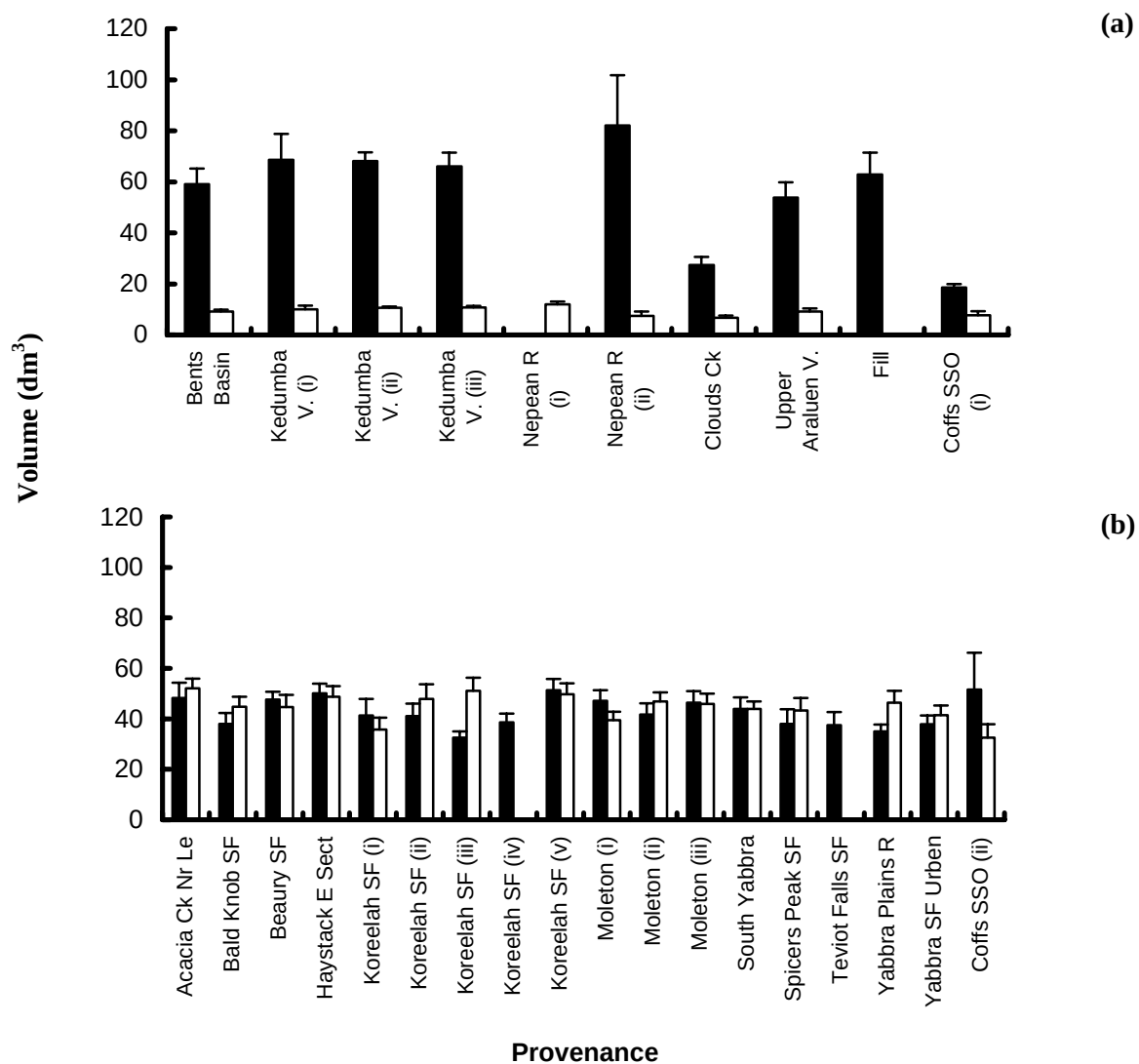


Figure 3.6 Tree volume of class 2 provenances in 1999. (a) *E. benthamii* seed orchard and (b) *E. dunnii* seed orchard at Barclay (■) and Crossley (□). Coffs Harbour SSO are the *E. grandis* reference seedlots.

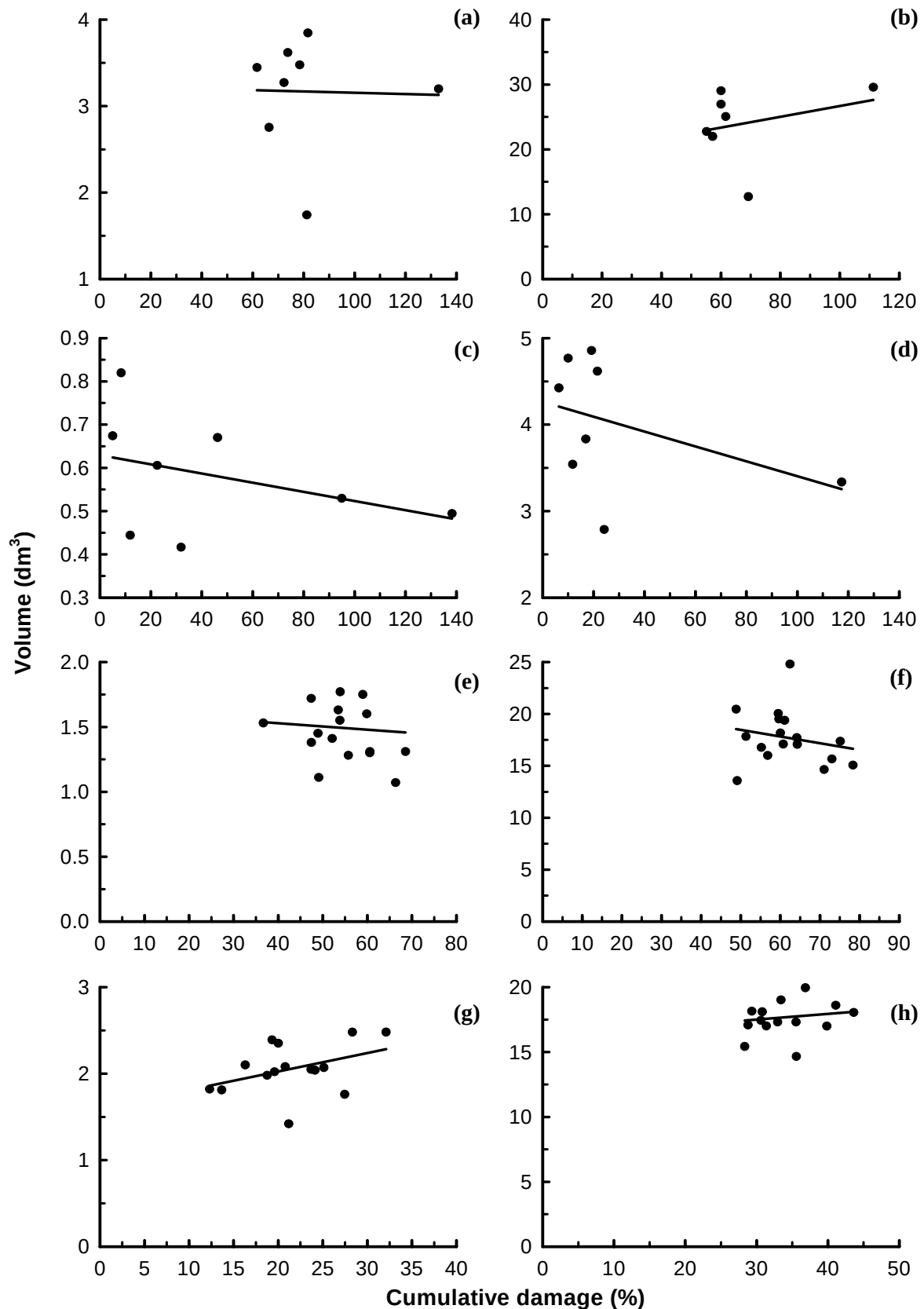


Figure 3.7

Plots of seedlot volume versus cumulative seedlot damage for *E. benthamii* (a)-(d) and *E. dunnii* (e)-(h) seed orchards in 1998. (a) and (e) Height class 1 and (b) and (f) Height class 2 seedlots at Barclay. (c) and (g) Height class 1 and (d) and (h) Height class 2 at Crossley. The fitted lines indicate the trend of the data but are not significant ($P > 0.05$). See Table 3.7 for definitions of height classes.

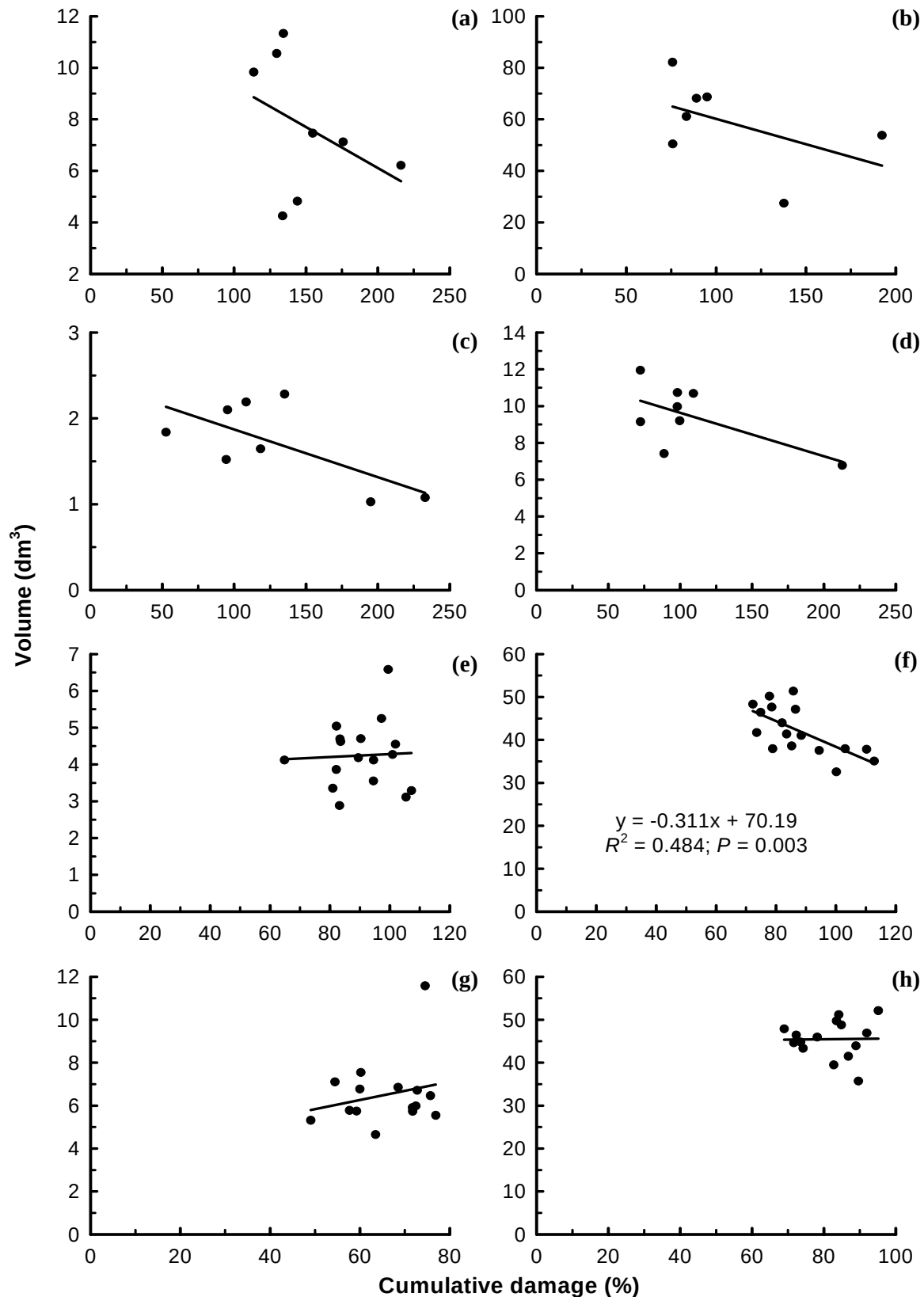


Figure 3.8 Plots of seedlot volume versus cumulative seedlot damage for *E. benthamii* (a)-(d) and *E. dunnii* (e)-(h) seed orchards in 1999. (a) and (e) Height class 1 and (b) and (f) Height class 2 seedlots at Barclay. (c) and (g) Height class 1 and (d) and (h) Height class 2 at Crossley. Except for (f) the fitted lines indicate the trend of the data but are not significant ($P > 0.05$). See Table 3.7 for definitions of height classes.

Table 3.9 Performance ranks of *E. benthamii* and *E. dunnii* seed orchard in 1999

Seed orchard	Species	Provenance	Barclay		Crossley		Mean (Class 2)
			Class 1	Class 2	Class 1	Class 2	
<i>E. benthamii</i>	<i>E. benthamii</i>	Bents Basin	3	5	5	6	5.5
		Kedumba V. (i)	6	2	2	4	3.0
		Kedumba V. (ii)	2	3	1	3	3.0
		Kedumba V. (iii)	4	4	3	2	3.0
		Nepean R (i)	8	-	8	1	1
		Nepean R (ii)	1	1	4	7	4.0
	<i>E. dorrigoensis</i>	Clouds Ck	5	7	7	8	7.5
	<i>E. kartzoffiana</i>	Upper Araluen Valley	7	6	6	5	5.5
	<i>E. grandis</i>	Coffs SSO (i)	7	8	7	7	-
<i>E. dunnii</i>	<i>E. dunnii</i>	Acacia Ck	17	3	14	1	2.0
		Bald Knob SF	10	12	1	9	10.5
		Beaury SF	6	4	7	10	7.0
		Haystack E	16	2	5	4	3.0
		Koreelah SF (i)	13	9	13	15	12.0
		Koreelah SF (ii)	9	10	8	5	7.5
		Koreelah SF (iii)	4	17	12	2	9.5
		Koreelah SF (iv)	8	11	-	-	11.0
		Koreelah SF (v)	7	1	9	3	2.0
		Moleton (i)	2	5	10	14	9.5
		Moleton (ii)	14	8	11	6	7.0
		Moleton (iii)	5	6	3	8	7.0
		South Yabbra	11	7	2	11	9.0
		Spicers Peak SF	3	13	4	12	12.5
		Teviot Falls SF	12	15	-	-	15.0
		Yabbra Plains	15	16	6	7	11.5
		Yabbra SF Urban	1	14	15	13	13.5
	<i>E. grandis</i>	Coffs SSO (ii)	18	1	16	16	-

Ranks are based on mean provenance volume and range from 1 (largest) to 17 (smallest). The *E. grandis* reference seedlots were excluded from the ranks. The values listed for *E. grandis* are included for comparison and indicate where the reference seedlots would rank if they were included.

Eucalyptus benthamii, *E. dorrigoensis*, *E. dunnii*, and *E. kartzoffiana* are all restricted to limited natural ranges and the genetic material included in the study extensively cover all known distinct seed sources. With such extensive genetic material it would be expected that any variation found in insect resistance would be a realistic indication of inherent variation between and within the species. However, environmental factors, both abiotic and biotic can influence the magnitude and expression of insect resistance in plants (Panda and Khush 1995). The magnitude and extent of the within-site spatial variation at both sites was sufficient to make the analysis of insect resistance in these tree species difficult. Despite this some conclusions can be made, although they should be taken with caution.

Eucalyptus benthamii and its closely related species *E. dorrigoensis*, and *E. kartzoffiana* appear less resistant to insect attack than *E. dunnii*. Levels of cumulative damage to the *E. benthamii* seed orchards were higher than damage levels in the *E. dunnii* seed orchards. However, the insect herbivore attacking the orchards was also important in determining damage levels. Trees in the *E. benthamii* seed orchard were more susceptible to autumn gum moth attack than trees in the *E. dunnii* seed orchard, but the opposite was the case for susceptibility to leafblister sawfly. Overall autumn gum moth was the major insect herbivore during the trial. In particular, the Upper Araluen Valley

provenance of *E. kartzoffiana* was very susceptible to autumn gum moth and this tree species should not be planted in areas with a high probability of autumn gum moth attack.

Inherent variability to insect attack was greater between seedlots from the *E. benthamii* seed orchards than between seedlots from the *E. dunnii* seed orchard. However, the range of variation in damage to the *E. benthamii* seed orchard provenances was only moderate and little evidence was found for a relationship between insect damage and plant growth for either seed orchard. In fact, both annual and cumulative damage levels to all seed orchards over the four years of the study were low to moderate. In artificial defoliation studies on *E. globulus* in Western Australia, Abbot and Wills (1996) found that depending on when it occurred within a year, annual defoliation levels of 50% may have no significant impact on plant growth. Only when such levels of defoliation occurred in autumn (March) was there an impact on growth. Other species of eucalypts, such as *E. regnans* F.Muell (Candy *et al.* 1992) and *E. grandis* (Carne *et al.* 1974), are equally robust in compensating for defoliation. It may have been that defoliation levels observed in this study were not large enough to have measurable impacts on growth.

However the confounding effect of the within-site variation at Barclay and Crossley on both insect damage levels and plant growth can not be discounted when considering the results. The large changes in soil profile across the sites tended to explain variation in plant size better than differences in inherent growth among seedlots, confounding analysis of the impact of insect damage on growth. As other results in this report show, insects such as autumn gum moth and Christmas beetle may preferentially attack trees of certain sizes. Any factor that influences the size distribution of plant populations being fed on by such insects may also influence total damage levels by altering the proportion of susceptible trees in the population. It is likely that the size and extent of the spatial variation masked any interaction between insect damage and plant growth.

Allowing for the impact of spatial variation on insect damage, the *E. benthamii* seed orchard seedlots appear to offer more potential for future genetic improvement in insect resistance than seedlots from the *E. dunnii* seed orchards. Balanced against this is the generally lower level of overall susceptibility to insect damage of *E. dunnii*. Also the two species showed different patterns of resistance to the two main insect herbivores active during this study, with *E. benthamii* more susceptible to autumn gum moth and *E. dunnii* more susceptible to leafblister sawfly.

More work is needed to quantify the potential of these species for genetic improvement in insect resistance. The current trial was designed primarily as seed orchards with assessment of insect impacts as a secondary feature. While some variation in seedlot resistance to insect damage has been identified, further experiments designed specifically to examine insect damage and resistance are now required. Such experiments would include insect exclusion treatments and possibly other treatments to test how management practices such as pruning, thinning and irrigation levels may alter the level of insect damage.

4 Within species variation in insect damage and growth in *Eucalyptus globulus*

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Summary

This chapter^{*} examines (i) within and between-provenance variation in susceptibility to insects in *Eucalyptus globulus* Labill., and (ii) relationships between insect damage and tree growth. This was achieved by planting seedlings of 18 provenances of *E. globulus* from south-east Australia in a common garden and measuring tree growth and insect damage.

Christmas beetles (*Anoplognathus* spp.) were the dominant herbivores during this experiment, with 99% of trees suffering some damage by these species. Defoliation by Christmas beetles ranged from 0% to 90%.

Provenances of *E. globulus* from Tasmania and the Bass Strait islands, which have previously shown resistance to autumn gum moth (*Mnesampela privata* (Guenée)) and leafblister sawfly (*Phylacteophaga froggatti* Riek), tended to show cross-resistance to Christmas beetle. Both within and between-provenance variation in resistance to attack by Christmas beetle and other insects was found. Insect damage tended to have a negative impact on tree growth.

Introduction

Plants show considerable variation in growth and susceptibility to herbivores both within and between genotypes (Bryant *et al.* 1983; Coley *et al.* 1985; Denno and McClure 1983; Herms and Mattson 1992). It has been hypothesised that variation in susceptibility to herbivores is largely determined by variation in amounts and types of plant secondary metabolites (Fraenkel 1959). Moreover, it is widely accepted that there is a trade-off between plant growth and chemical defence because these functions compete for limiting resources (Bazzaz *et al.* 1987; Chapin *et al.* 1990). Thus, fast growing plants (species, populations, or individuals) are hypothesised to be more susceptible to herbivores than slow growing plants (species, populations, and individuals).

Trade-offs between defence and growth potentially pose an important practical problem in agriculture and forestry, where fast growing genotypes with high yield have been artificially selected and where growth and yield are enhanced by irrigation and fertiliser applications. Moreover, the level of spatial variation in plant chemical defence in crop fields and plantations is typically much less than that in natural environments (Denno and McClure 1983). Once pest species establish themselves, they can spread quickly and cause considerable damage to crops or plantation trees. To compensate for the reduced level natural resistance to insect attack, insecticides are used to control pests in fields and plantations. However, periodic large-scale preventative spraying is costly both to farmers and plantation owners and to the general public through the hidden cost of environmental damage. This

* A modified version of this chapter was published in 2002 in *Agricultural and Forest Entomology* **4**: 109–115.

also raises the spectra of the pest species developing resistance. To optimise the effects of spraying, regular monitoring of population levels of pests has been suggested for certain pest species (Candy *et al.* 1992b; Elliott *et al.* 1992). However, the cost of conducting surveys to detect pest establishment before substantial damage is incurred may be prohibitive. One possible approach to reducing the dependence on the use of insecticides is to incorporate genetically resistant plants in agriculture and forestry (Floyd and Farrow 1994). Moderate increases in resistance to insect pests might result in equivalent or enhanced growth compared with susceptible genotypes if the reduction in growth due to resistance in resistant plants was less than the growth reduction due to insect damage in susceptible plants. Also, if a total loss of crops or plantation trees due to pest damage can be avoided by the use of resistant (but slightly slower growing) genotypes, then the net benefit of planting resistant genotypes may be greater than planting susceptible (but fast growing) genotypes.

Eucalyptus globulus Labill. is an important plantation species in southern Australia. This chapter examines the relationship between growth and susceptibility to insect pests of the species both within and between provenances. Considerable variation in susceptibility to various insect pests in *Eucalyptus* spp. has been documented. Between and within species variation has been recorded in *E. melliodora* A.Cunn. ex Schauer, *E. conica* Deane & Maiden, *E. sideroxylon* A.Cunn. ex Woolls, *E. viminalis* Labill., *E. blakelyi* Maiden, *E. caliginosa* Blakely & McKie, and *E. camaldulensis* Dehnh. (Edwards *et al.* 1993; Edwards *et al.* 1990; Lowman and Heatwole 1987). Within species variation is known in *E. regnans* F.Muell., *E. nitens* (Deane & Maiden) Maiden, *E. blakelyi* and *E. camaldulensis* (Floyd *et al.* 1994; Raymond 1995; Stone and Bacon 1994b); and within and between provenance variation in *E. globulus* (Farrow *et al.* 1994). These studies have shown that within a species, susceptible individuals or provenances suffer at least twice the amount of damage by insect pests as resistant individuals or provenances.

Results presented here directly follow from a previous study of variation in resistance to insect herbivores in *E. globulus* by Farrow *et al.* (1994). The main results of that study were:

1. Provenances from Tasmania and the Bass Strait islands were more resistant to herbivores than provenances from mainland Australia (Victoria); and
2. The resistant provenances showed cross-resistance to two insect species, autumn gum moth (*Mnesampela privata* Guenée (Lepidoptera: Geometridae)) and leafblister sawfly (*Phylacteophaga froggatti* Riek (Hymenoptera: Pergidae)). However, tree growth was not included in the previous study.

The data presented here adds to the Farrow *et al.* (1994) study by:

1. Comparing 18 provenances representing all four subspecies from Tasmania, the Bass Strait islands, and the mainland (Victoria and NSW);
2. Examining the relationships between growth and resistance to insect pests;
3. Comparing within and between provenance variation in growth and resistance to insect pests; and
4. Investigating cross-resistance to another pest, Christmas beetle *Anoplognathus* spp. (Coleoptera, Scarabaeidae).

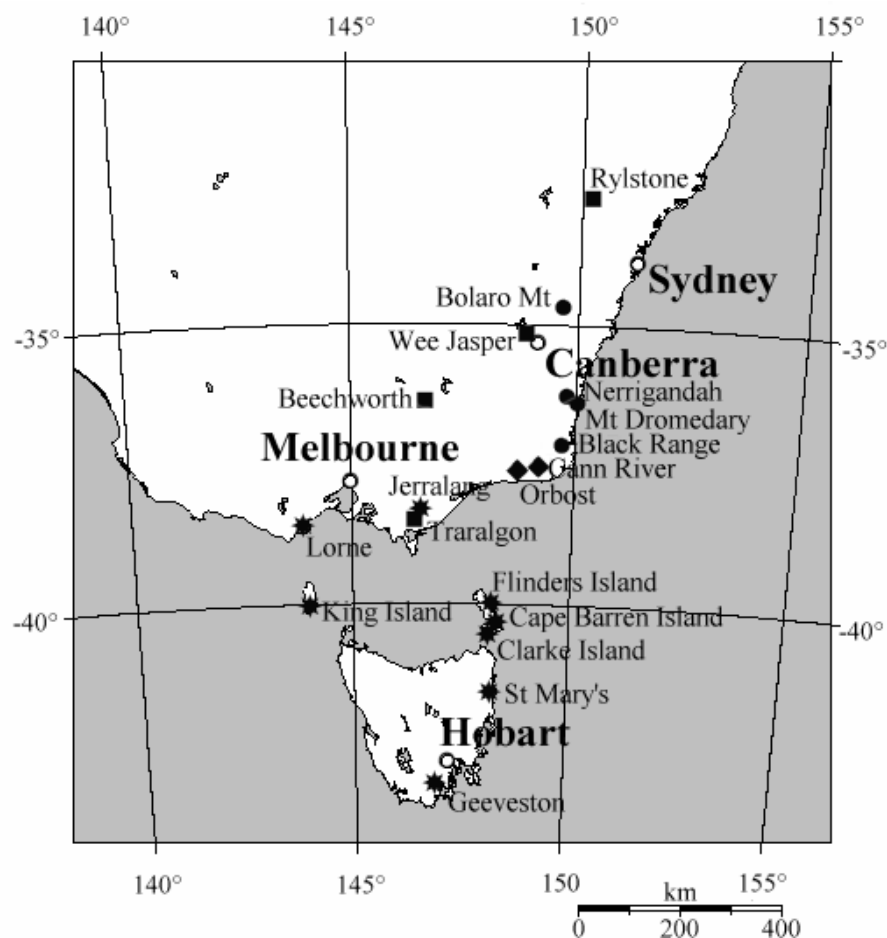


Figure 4.1 Map showing locations of 18 provenances of *E. globulus* used in this study. Key to *Eucalyptus* subspecies: *E. globulus bicostata* ■, *E. globulus globulus* ★, *E. globulus maidenii* ● and *E. globulus pseudoglobulus* ◆.

Materials and methods

Study organisms

Eucalyptus globulus occurs naturally in south-east Australia and consists of four subspecies (Kirkpatrick 1974) (Figure 4.1). Eighteen provenances are included in this study, comprising eight provenances of *E. globulus globulus* Labill., four provenances of *E. globulus bicostata* (Maiden) Kirkpatr., four provenances of *E. globulus maidenii* (F. Muell.) and two provenances of *E. globulus pseudoglobulus* (Naudin ex Maiden) Kirkpatr. Provenance details are given in Table 4.1. Except for *E. g. bicostata*, which occurs predominantly on plateaus, *E. globulus* tends to occur on mid to lower slopes in sheltered valleys. All subspecies occur in areas with 600–1400 mm rainfall and some frosts each winter.

Eucalyptus globulus is considered to be a fast growing species among eucalypts and is an important species for the plantation industry in southern Australia because of its high fibre quality (Cotterill and MacRae 1997). All subspecies typically grow to 30–45 m in height, and up to 75 m under favourable conditions. Severe herbivory by autumn gum moth and leafblister sawfly on *E. globulus* plantations have previously been reported (Elliott and Bashford 1978; Farrow *et al.* 1994; Neumann 1993).

Christmas beetles are common herbivores on several *Eucalyptus* species on farmland and totally defoliate some trees in some years (Carne *et al.* 1974b; Edwards *et al.* 1993; Edwards *et al.* 1990). At least seven species of Christmas beetle have been observed at and around the study site in Canberra (*A. pallidicollis* Blanchard, *A. velutinus* Boisduval, *A. chloropyrus* (Drapiez), *A. hirsutus* Burmeister, *A. montanus* Macleay, *A. suturalis* Boisduval, and *A. viriditarsis* Leach). Drought in late spring/early summer is correlated with low abundance of Christmas beetles. (Carne *et al.* 1981). The adults feed on *Eucalyptus* leaves, and the larvae feed on roots of grasses and crop plants. Severe defoliation of farmland *Eucalyptus* trees has been considered as a result of changes in land use practice. Increased areas of farmland provide favourable conditions for larval growth, and reduced areas of woodland resulted in high concentration of adults on a small number of farmland trees (Ohmart and Edwards 1991).

Table 4.1 Details of *E. globulus* seedlots used at the Lyneham Ridge site

Species	Provenance	Seedlot	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	No of parents
<i>E. globulus bicostata</i>	Beechworth	16369	36° 22.8'	146° 42.0'	750	10
<i>E. globulus bicostata</i>	Rylstone	16305	32° 43.2'	150° 13.2'	1100	10
<i>E. globulus bicostata</i>	Traralgon	15270	38° 24.0'	146° 30.0'	480	6
<i>E. globulus bicostata</i>	Wee Jasper	15269	35° 10.8'	148° 54.0'	870	8
<i>E. globulus globulus</i>	12.1K S Lorne PO	16852	38° 36.0'	143° 54.0'	200	7
<i>E. globulus globulus</i>	Cape Barren Island	16416	40° 19.2'	148° 18.0'	60	5
<i>E. globulus globulus</i>	Clarke Island	17608	40° 31.8'	148° 07.8'	40	6
<i>E. globulus globulus</i>	Flinders Island	16417	39° 58.8'	148° 10.8'	60	1
<i>E. globulus globulus</i>	Geeveston	16476	43° 12.0'	146° 54.0'	250	7
<i>E. globulus globulus</i>	Jerralang	16319	38° 19.2'	146° 33.0'	220	27
<i>E. globulus globulus</i>	King Island	16424	40° 00.0'	144° 00.0'	40	11
<i>E. globulus globulus</i>	St Mary's	16474	41° 34.2'	148° 12.0'	400	5
<i>E. globulus maidenii</i>	Black Range	17742	37° 10.2'	149° 40.8'	320	37
<i>E. globulus maidenii</i>	Bolaro Mt	15917	34° 40.2'	150° 01.8'	360	7
<i>E. globulus maidenii</i>	Mt Dromedary	17743	36° 22.2'	150° 01.8'	400	3
<i>E. globulus maidenii</i>	Nerrigundah	17769	36° 15.0'	149° 46.2'	245	3
<i>E. globulus pseudoglobulus</i>	Cann River	15271	37° 30.0'	149° 10.8'	140	3
<i>E. globulus pseudoglobulus</i>	Orbost	18111	37° 36.0'	148° 45.0'	370	24

Plantation experiment

Seeds were obtained from the Australian Tree Seed Centre, CSIRO Forestry and Forest Products, Canberra, Australian Capital Territory, Australia. Seedlings were planted at Lyneham Ridge, Canberra, Australian Capital Territory (35°14'S, 149°07'E; 620 m a.s.l.) in May 1994. The study site is located on a small ridge oriented north-south, and the seedlings were planted on an east-facing slope near the top of the ridge. The site is divided into six blocks, located along the ridgeline. Within each block, there are 18 plots, one plot for each provenance: six rows down the slope × three plots along the ridgeline. Four seedlings were planted in each plot. Provenances were assigned randomly to the plots. Seedlings were planted 2.5 m apart in each row, and rows were 4 m apart. Two rows of seedlings were planted as a buffer around the experimental blocks. Three blocks were sprayed with insecticide, and three others were left unsprayed. Spraying treatment was randomly assigned to each block. At the time of planting, seedling height ranged from 14 to 51 cm (mean = 34 cm, SD = 7 cm, $n = 432$).

Height and stem diameter of each plant were measured at the time of planting (May 1994), June 1995, February 1996, August 1996, September 1997, September 1998 and September 1999. Initially tree

height was measured to the nearest 0.1 m using graduated height poles. As the plantations developed this became impractical and the poles were replaced with an electronic measuring device (VERTEX). The standard measure of tree girth was diameter at breast height (DBH) which is defined as the diameter at 1.3 m above ground level. However, this was only practical when trees were at least 2–2.5 m tall. As we were interested in detecting long term impacts of insect damage on young trees it was necessary to measure tree diameter at least annually from the time the trees were planted. When trees were too small for DBH measurements, diameter at ground level (DGL) was used as an alternative. Individual tree volume (V in cm^3) was calculated using the conical volume equation:

$$V = \frac{(DBH / 2)^2 \times Ht \times \pi}{3 \times 10^3}$$

where Ht = height in cm and DBH is diameter at breast height in cm. A square root transformation of volume was used in all statistical analysis. Only a subset of trees was included in the volume calculations. Trees with multiple trunks or trees that had suffered substantial trunk or crown damage were excluded, as the conical equation is not a good estimator of volume for these trees. Furthermore, in commercial plantations these trees would normally be thinned as part of routine maintenance. Relative growth rate (RGR in $\text{cm}^3 \text{cm}^{-3} \text{yr}^{-1}$) of plants, corrected for the initial plant size, was calculated as:

$$RGR = 365 \times \frac{V_{t+1} - V_t}{V_t \times (t_{+1} - t)}$$

where V_t and V_{t+1} = square root transformed volume at time t and t_{+1} respectively and t = date of initial measurement and t_{+1} = date of final measurement.

The extent of insect damage was visually assessed at least every six months starting June 1995. Damage assessments were scheduled so as to quantify damage before, during, and after peak periods of herbivory by Christmas beetles and autumn gum moth. Herbivory on juvenile and adult leaves was assessed separately, and herbivory by each insect species was recorded separately. To ensure consistency, the same observers conducted all damage assessments. Damage levels for each insect species were scored as percentages on a scale from 0–100% in 10% intervals between 10% and 90%, with finer graduations near 0% and 100% (0%, 1%, 5% and 95%, 99%). Separately assessing damage by different insect species was possible because each insect species produced characteristic damage.

Statistical analyses

We examined the effects of spraying insecticide and differences among provenances in growth and resistance to insects. As the study progressed, it became apparent that plants on the top of the ridge were growing slower than those down the slope. Therefore, we first examined effects of plant location using restricted maximum likelihood analysis (REML: (Corbeil and Searle 1976)). Location of plants, specified by block, row, plot, and tree position, was used as the random effect, and insecticide treatment and population were treated as the fixed effects. Plant growth was significantly affected by location, especially that specified by row and row $\times$ block. Therefore, we estimated mean growth rates of plants for each population using REML. Significance was tested using a likelihood ratio test based on the difference (Δdev) between log-likelihoods calculated for a full model, which included all terms, and a nested sub model from which the terms of interest were dropped (Genstat 5 Committee 1993). Insect damage was not, however, affected by the location of plants, and therefore, we used analysis of variance (ANOVA) to estimate mean damage for each population.

For the analysis at the level of individuals within each population, we used residuals from trend surface regressions (Legendre 1990; Legendre 1993) with the plant growth as the response variable and row, block, and row $\times$ block as explanatory variables. The residuals from the trend surface

regressions represent variation in plant growth rates associated with factors other than the physical location of plants within the experimental site. All statistical analyses were performed using Genstat (Genstat 5 Committee 1993) and SAS (SAS Institute 1989).

Results

Insect damage

There was approximately a three-fold difference in cumulative damage by insects among the 18 provenances of *E. globulus* during the five years of study (Figure 4.2a). No clear trend in insect damage with respect to geographic locations or subspecies was observed (Table 4.2).

Table 4.2 Insect resistance ranks of subspecies and provenances of *Eucalyptus globulus* at Lyneham Ridge. Ranks are based on mean cumulative damage and range from 1 (least damage) to 18 (most damage)

Subspecies	Provenances	Geographical area	Rank
<i>E. g. globulus</i>	Geeveston	Tasmania	1
<i>E. g. bicostata</i>	Wee Jasper	NSW	2
<i>E. g. bicostata</i>	Rylstone	NSW	3
<i>E. g. bicostata</i>	Beechworth	Victoria	4
<i>E. g. globulus</i>	King Is	Bass Strait	5
<i>E. g. maidenii</i>	Bolaro Mt	NSW	6
<i>E. g. maidenii</i>	Nerrigandah	NSW	7
<i>E. g. globulus</i>	Cape Barren Island	Tasmania	8
<i>E. g. pseudoglobulus</i>	Orbost	Victoria	9
<i>E. g. pseudoglobulus</i>	Cann River	Victoria	10
<i>E. g. globulus</i>	Flinders Is	Tasmania	11
<i>E. g. bicostata</i>	Traralgon	Victoria	12
<i>E. g. maidenii</i>	Black Range	NSW	13
<i>E. g. globulus</i>	Clarke Island	Bass Strait	14
<i>E. g. maidenii</i>	Mt Dromedary	NSW	15
<i>E. g. globulus</i>	Jeeralang	Victoria	16
<i>E. g. globulus</i>	Lorne	Victoria	17
<i>E. g. globulus</i>	St Mary's	Tasmania	18

The largest damage event occurred between December 1995 and January 1996 and was caused by Christmas beetles. All except one out of 186 plants in the unsprayed treatment were affected, and levels of defoliation reach 85% on some of the plants (mean = 54%, SD = 20%, $n = 186$). Zero to 88% of the total cumulative damage was caused by this event (mean = 32%, SD = 16%, $n = 186$). Provenances from Tasmania and Bass Strait Islands tended to receive less damage than the mainland provenances (Figure 4.2b). However, provenances from Cape Barren Island and Flinders Island received comparatively more damage in subsequent years. When individual trees were examined separately, very short trees tended to escape Christmas beetle damage while taller trees tended to receive more damage (Figure 4.3). However, as the plantation aged and the trees became taller, more severe damage was found on trees with intermediate height.

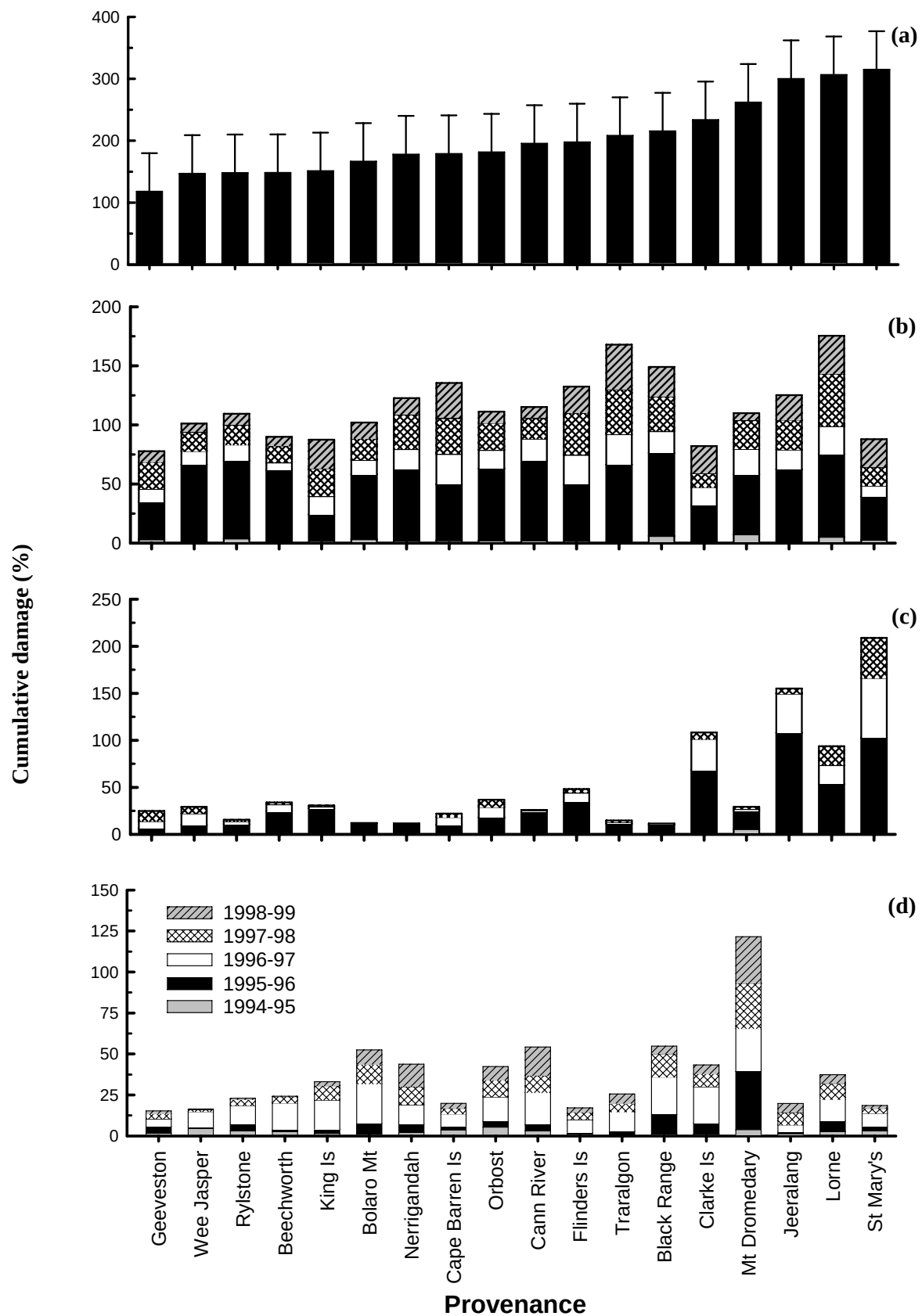


Figure 4.2 Insect damage on 18 provenances of *E. globulus*. (a) Cumulative total damage (Mean $\pm$ SE) between 1994 and 99. (b) Damage by *Anoplognathus* spp. (c) Damage by *Eriococcus* spp. No damage in 1998–99. (d) Damage by herbivores other than *Anoplognathus* spp.

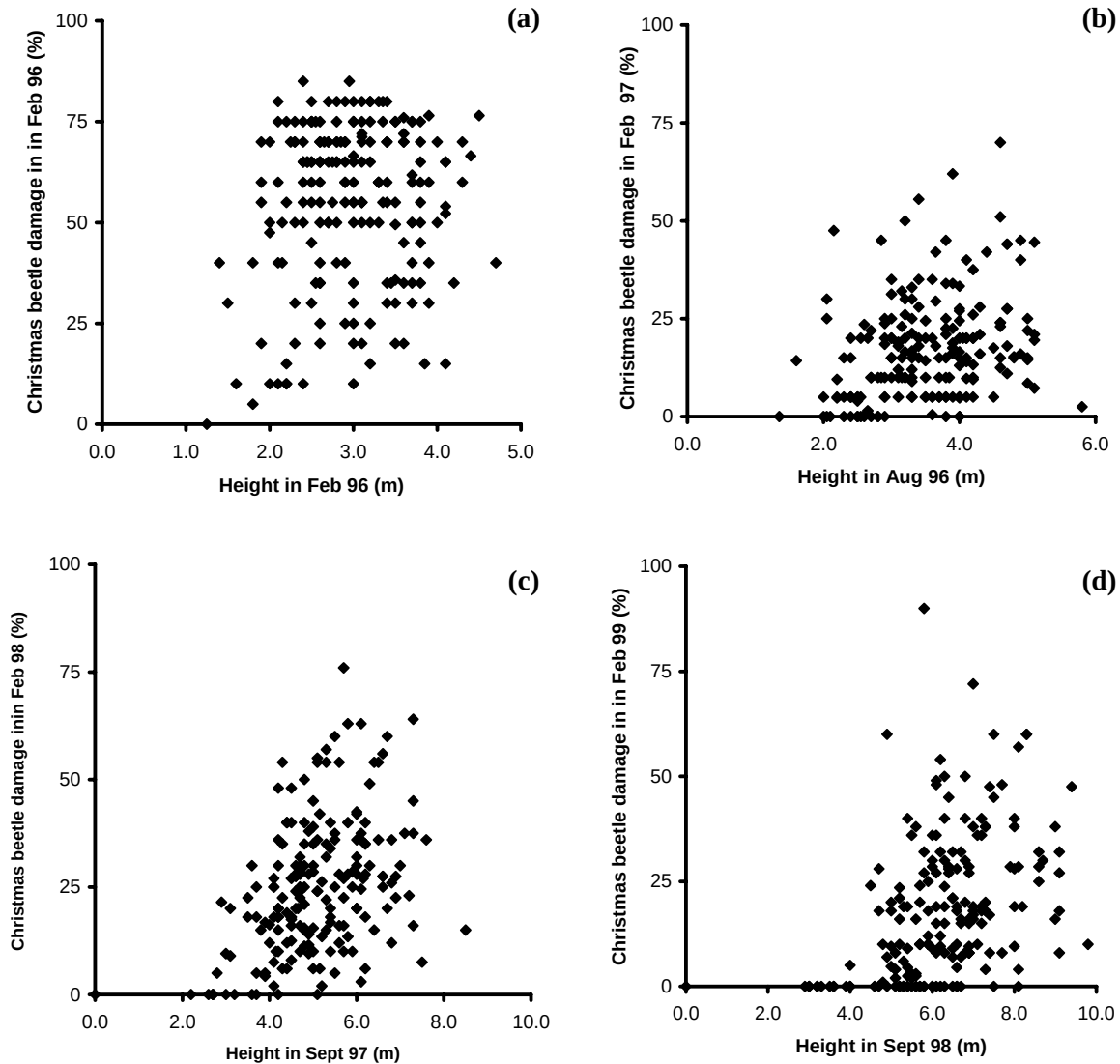


Figure 4.3 Relationship between tree height in the previous year and damage by Christmas beetles (*Anoplognathus* spp.). Relationship (a) between damage and height in February 1996, the first year of attack., (b) Height in 1996 and damage in 1997, (c) Height in 1997 and damage in 1998 and (d) Height in 1999 and damage in 1998.

Scale insects (*Eriococcus* spp.) also caused extensive damage in 1996 and 1997 (Figure 4.2c). Provenances of *E. g. globulus*, especially Jeeralang, Lorne, Clarke Island, and St. Mary's, were affected comparatively more than provenances of other subspecies. The provenance from Mt. Dromedary was heavily damaged by autumn gum moth, leafblister sawfly, *Paropsis atomaria* Olivier (Coleoptera: Chrysomelidae), and *Gonipterus scutellatus* (Gyllenhal) (Coleoptera: Curculionidae), between 1997 and 99 (Figure 4.2d).

Plant growth

Volume of sprayed plants was significantly different among the 18 provenances (Figure 4.4a) (REML testing for the provenance effect: $\Delta dev = 49$, $df. = 17$, $P < 0.001$). There was a four-fold difference in mean plant volume. Provenances of *E. g. bicostata* and *E. g. globulus* showed variable mean plant volume, while those of *E. g. maidenii* and *E. g. pseudoglobulus* tended to be uniformly small. The top five provenances with large volume are listed in Table 4.3.

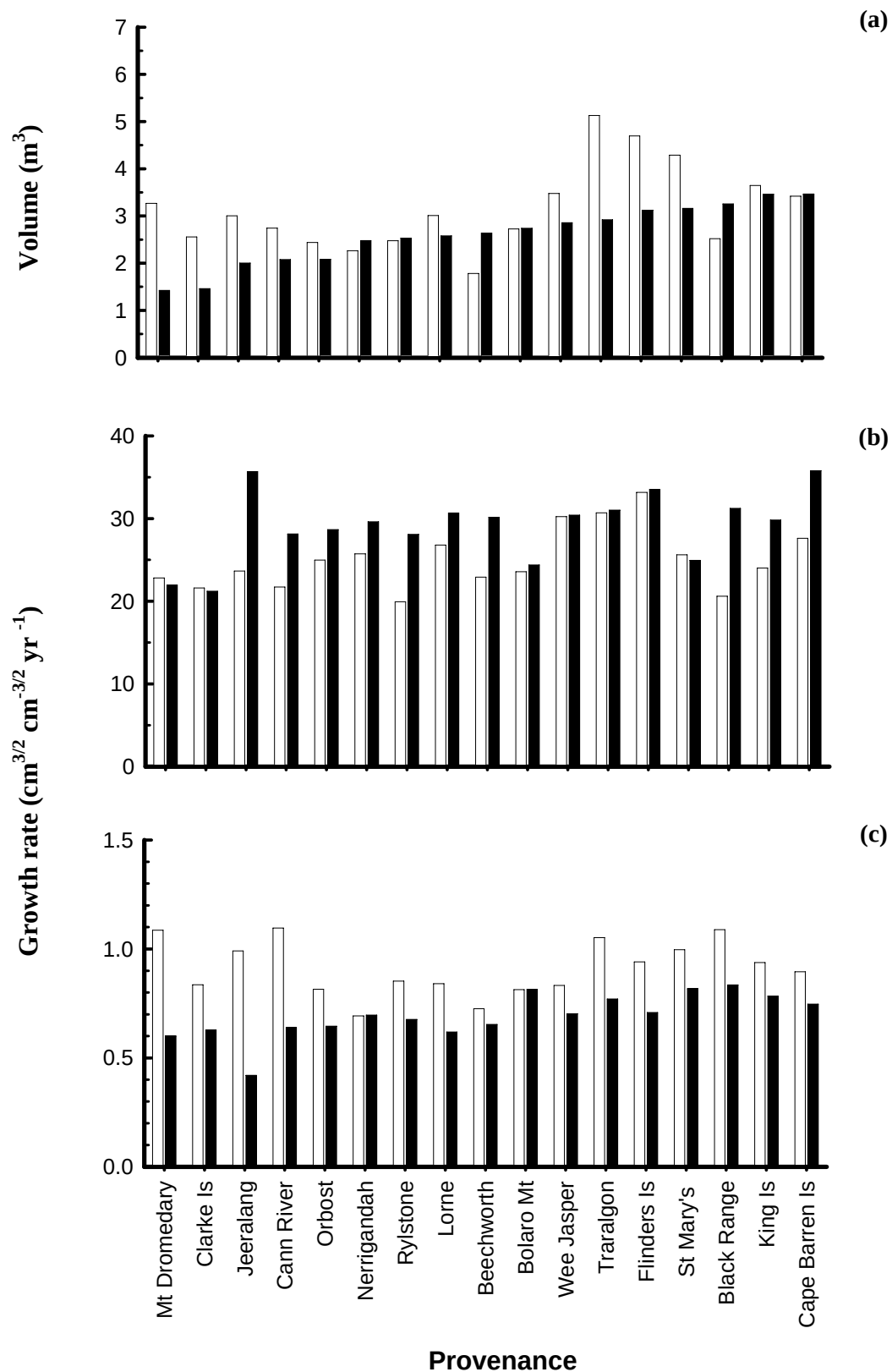


Figure 4.4 Performance of 18 provenances of sprayed (□) and unsprayed (■) *E. globulus*. (a) Volume after 5 years and 4 months (b) Relative growth rate between planting and the major damage by Christmas beetles. (May 1994 – February 1996). (c) Relative growth rate after the major damage by Christmas beetles (February 1996 – September 1999).

Table 4.3 Performance of subspecies and provenances of *Eucalyptus globulus* at Lyneham Ridge. Ranks are based on volume in 1999 and range from 1 (largest) to 18 (smallest)

Subspecies	Provenances	Geographical area	Rank
<i>E. g. globulus</i>	Geeveston	Tasmania	1
<i>E. g. globulus</i>	Cape Barren Is	Tasmania	2
<i>E. g. globulus</i>	King Is	Bass Strait	3
<i>E. g. maidenii</i>	Black Range	NSW	4
<i>E. g. globulus</i>	St Mary's	Tasmania	5
<i>E. g. globulus</i>	Flinders Is	Tasmania	6
<i>E. g. bicostata</i>	Traralgon	Victoria	7
<i>E. g. bicostata</i>	Wee Jasper	NSW	8
<i>E. g. maidenii</i>	Bolaro Mt	NSW	9
<i>E. g. bicostata</i>	Beechworth	Victoria	10
<i>E. g. globulus</i>	Lorne	Victoria	11
<i>E. g. bicostata</i>	Rylstone	NSW	12
<i>E. g. maidenii</i>	Nerrigandah	NSW	13
<i>E. g. pseudoglobulus</i>	Orbost	Victoria	14
<i>E. g. pseudoglobulus</i>	Cann River	Victoria	15
<i>E. g. globulus</i>	Jeeralang	Victoria	16
<i>E. g. globulus</i>	Clarke Is	Bass Strait	17
<i>E. g. maidenii</i>	Mt Dromedary	NSW	18

Insect damage did reduce plant volume in 12 out of 18 provenances (Figure 4.4a) (REML testing for the overall effect of spraying: $\Delta dev = 4.5$, $df = 1$, $P = 0.03$). In the first one and half years of the trial, when insect damage was minimal, mean plant growth rates tended to be greater in unsprayed treatment than in sprayed treatment (Figure 4.4b). This was due to damage by insecticides in the sprayed treatment. However, sixteen out of 18 provenances show greater mean plant growth rates in sprayed than unsprayed treatment after the major damage by Christmas beetles between December 1995 and January 1996 (Figure 4.4c).

Based on mean plant volume of sprayed and unsprayed treatments, we calculated a predicted rank of plant volume under different probabilities of occurrence of insect damage (Table 4.4). Predicted mean plant volume of a provenance when the probability of occurrence of insect damage is p is:

$$\text{Volume}(p) = [\text{mean volume of unsprayed plants} \times p + \text{mean volume of sprayed trees} \times (1 - p)] / 2.$$

Regardless of the probability of occurrence of insect damage, the provenance from Geeveston is predicted to be the best provenance in terms of plant volume after five years. Provenances from Traralgon, Flinders Island, and St. Mary's are predicted to be good provenances when the probability of insect damage is low and Black Range is predicted to be good provenances when the probability of occurrence of insect damage is high.

Discussion

Previous plantation experiments had shown that provenances of *E. globulus* from Tasmania and the Bass Strait islands were less susceptible autumn gum moth, *M. privata*, and leafblister sawfly, *P. froggatti*, compared with provenances from mainland Australia (Farrow *et al.* 1994). Results of this study showed that some provenances from Tasmania and Bass Strait islands were also less susceptible to Christmas beetles, *Anoplognathus* spp. However, there was no clear relationship between damage by Christmas beetles and that by other herbivores (e.g. autumn gum moth) in this study. It is possible that differential resistance to insects can be observed only when damage levels are above a certain

threshold, as evident from damage by Christmas beetles in the 1996–97 season. Damage by herbivores other than Christmas beetles at any one time was much smaller than that by the beetles in the summer of 1995–96 or damage by autumn gum moth and leafblister sawfly described in Farrow *et al.* (1994).

In addition to between-provenance variation, we observed between-individual variation in plant growth and resistance to Christmas beetle attack. There has been a suggestion that Christmas beetles tend to be attracted to tall trees in a plantation (M. J. Steinbauer, personal communication). However, at least in this study, while early damage tended to be greatest on taller, as the plantation aged and trees became taller most damage tended to occur to those trees intermediate in height.

Alternatively, differences among individual trees within each provenance may be due to genetic differences. Although we did not examine the heritability of plant growth and resistance to insect herbivores, a study using *E. regnans* and *E. nitens* showed that the resistance of these two species to eucalypt leaf beetle, *Chrysophtharta bimaculata* Olivier (Coleoptera: Chrysomelidae), was heritable (Raymond 1995). The next step in selection of herbivore resistant *E. globulus* will be to examine the heritability of plant growth and resistance to herbivores.

Table 4.4 Predicted rank order of 18 provenances of *E. globulus* at different probability of insect attack

Provenance	Probability of insect attack										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Beechworth	18	18	18	18	17	17	15	13	12	11	10
Black Range	14	13	12	10	9	8	8	8	7	6	4
Bolaro Mt	12	11	11	9	10	10	10	9	9	9	9
Cann River	11	12	13	13	13	13	14	15	14	14	15
Cape Barren Is	7	6	6	6	6	6	6	6	3	3	2
Clarke Is	13	15	16	17	18	18	18	18	18	18	17
Flinders Is	3	3	3	3	3	3	3	2	4	5	6
Geeveston	1	1	1	1	1	1	1	1	1	1	1
Jeeralang	10	10	10	11	11	12	13	14	15	16	16
King Is	5	5	5	5	5	5	5	4	2	2	3
Lorne	9	9	8	8	8	9	9	10	10	10	11
Mt Dromedary	8	8	9	12	14	16	17	17	17	17	18
Nerrigundah	17	17	17	16	15	14	12	12	13	13	13
Orbost	16	16	15	15	16	15	16	16	16	15	14
Rylstone	15	14	14	14	12	11	11	11	11	12	12
St Mary's	4	4	4	4	4	4	4	5	5	4	5
Taralgon	2	2	2	2	2	2	2	3	6	7	7
Wee Jasper	6	7	7	7	7	7	7	7	8	8	8

Although the provenance from Geeveston showed fast mean plant growth and resistance to insects, fast growing individuals and provenances, in general, tended to be more susceptible to insects. This result, combined with reduced growth due to insect damage, may pose a practical problem for plantation owners because fast growing trees are likely to receive more insect damage than slow growing trees. Therefore, selecting the fastest growing trees may not maximise the return if trees are attacked by insects. Unfortunately, insect outbreaks are highly variable in space and time. Perhaps, a safe option for plantation owners is to mix provenances which are less resistant but fast growing such as those from St. Mary's, Taralgon, and Flinders Island and provenances which are more resistant but slower growing such as those from King Island, Black Range, and Cape Barren Island. This would ensure that whatever the incidence of insect attack, at least some part of the plantation would remain productive.

Acknowledgments

We thank J. Dowse and R. Sutherland for field work, R. Cunningham and C. Donnelly for advice on REML and M. Michie for technical assistance. ACT Forests provided the site for the plantation experiment. Financial support was provided by the Joint Venture Agroforestry Program.

5 Effects of acute damage and chronic damage by insects on growth in *Eucalyptus globulus*

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Summary

This chapter examines the relationships between growth of *Eucalyptus globulus* and different types of insect damage. Specifically we examine the impacts of two types of damage—acute and chronic. Acute damage is defined as intense damage caused by Christmas beetles (*Anoplognathus* spp., Scarabaeidae: Coleoptera) occurring over a short period (a few days to two weeks each summer). Chronic damage is the less intense damage caused by other insect species and occurring over many months (three months or longer). Seedlings from 18 populations of *E. globulus* were planted in a common garden, and we measured growth and insect damage for five years. There was large inter- and intra-population variation in insect damage. All but one of 185 plants suffered acute damage from *Anoplognathus* spp., and up to 90% of foliage of a plant was damaged in any one year. Zero to 88% of total cumulative damage and zero to 100% of total annual damage was caused by *Anoplognathus* spp. Individual plants that tended to suffer severe chronic damage or acute damage in one year also suffered severe chronic damage or acute damage, respectively, the following year. In four of the five years, strong associations between variation in annual growth rates and variation in acute damage were found in populations with intermediate mean potential growth rates of plants and with severe mean acute damage.

Introduction

While phytophagous and sap-sucking insects reduce plant growth, not all insect damage has the same effect on plant growth. For example, evenly distributed defoliation results in a smaller reduction in the subsequent plant growth and reproduction than the same amount of defoliation concentrated on only one part of a plant (Marquis 1991; Marquis 1992; Mauricio *et al.* 1993; Price and Hutchings 1992). In nature, intra-crown variation in defoliation can be caused by spatial variation in insect population densities possibly due to spatial variation in plant leaf chemistry.

Insect populations vary not only in space but also in time. A number of phytophagous insects attack young leaves (Ayres and MacLean Jr. 1987; Coley 1980; Coley 1983; Coley and Aide 1991b; Landsberg 1988; Lowman 1985; Raupp and Denno 1983). Damage caused during leaf development is hypothesised to have stronger effects on plant growth and reproduction than that caused in other times (Harper 1989; Jurik and Cabot 1986; Krischik and Denno 1983; Mendoza *et al.* 1987); but see Haukioja *et al.* (1990). In certain parts of the world, plants also suffer from periodic or irregular insect outbreaks during which the entire plant or the entire landscape may be defoliated by a single species of insect (Edwards *et al.* 1993; Edwards *et al.* 1990; Tenow 1972). Also, damage can be intense (i.e., occurring in a relatively short period of time) or spread out over a long time (Landsberg 1990; Lowman and Heatwole 1992).

The purpose of this chapter is to report results of exploratory data analyses on relationships between growth of a long-lived plant species and acute and chronic insect damage. During a plantation trial in

south-east Australia to select for populations of Tasmanian blue gum (*Eucalyptus globulus* Labill.) which are insect resistant, the trial trees suffered both small amounts of damage throughout the trial and intense annual defoliation events by Christmas beetles (*Anoplognathus* spp., Coleoptera: Scarabaeidae) (Floyd *et al.* in prep). In this study, we define acute damage to be defoliation by *Anoplognathus* spp. that occurred annually in mid December to mid January and chronic damage to be damage by other species of insects. *Anoplognathus* spp. typically feed in large groups, and a group of beetles spend time feeding in a patch of trees (e.g. plantations) from a few days to a few weeks. In contrast, chronic damage by other insects such as scale insects (*Eriococcus* spp., Hemiptera: Eriococcidae) and autumn gum moth (*Mnesampela privata*: Geometridae, Lepidoptera) occurred over much longer time scale (3 months or longer) each year.

Methods

Study organism

Eucalyptus globulus occurs naturally in south-eastern Australia. Four subspecies have been recognised (Kirkpatrick 1974), and all four subspecies (18 populations or provenances) are included in this study (Figure 5.1): eight populations of *E. globulus globulus* Labill., four populations of *E. globulus bicostata* (Maiden) Kirkpatr., four populations of *E. globulus maidenii* (F. Muell.) and two populations of *E. globulus pseudoglobulus* (Naudin ex Maiden) Kirkpatr. Except for *E. g. bicostata*, which occurs predominantly on plateaus, *E. globulus* tends to occur on mid to lower slopes in sheltered valleys. New leaves are typically produced from early summer to mid autumn. Populations of *E. g. globulus* from Tasmania and the Bass Strait Islands have been shown to be cross resistant to at least three species of major insect pests in south-east Australia: autumn gum moth (*Mnesampela privata*, Geometridae: Lepidoptera) (Floyd *et al.* 1994), leaf blister sawfly (*Phylacteophaga froggatti*, Pergidae: Hymenoptera) (Farrow *et al.* 1994), and Christmas beetles (*Anoplognathus* spp.) (Floyd *et al.* in prep).

Anoplognathus species are common herbivores on several *Eucalyptus* species on farmland and totally defoliate some trees in some years (Carne *et al.* 1974b; Edwards *et al.* 1993; Edwards *et al.* 1990). At least seven species of *Anoplognathus* have been observed in and around the study site (*A. pallidicollis* Blanchard, *A. velutinus* Boisduval, *A. chloropyrus* (Drapiez), *A. hirsutus* Burmeister, *A. montanus* Macleay, *A. suturalis* Boisduval, and *A. viriditarsis* Leach). Adult beetles feed on *Eucalyptus* leaves, and larvae feed on roots of grasses and crop plants.

Plantation experiment

Seeds were obtained from the Australian Tree Seed Centre, CSIRO Forestry and Forest Products, Canberra, Australian Capital Territory, Australia. Seedlings were planted at Lyneham Ridge, Canberra, Australian Capital Territory (35°14'S, 149°07'E, 620 m a.s.l.) in May 1994. The study site is located on a small ridge oriented north-south, and the seedlings were planted on an east facing slope from the top of the ridge downwards. There are six blocks, located along the ridgeline. Within each block, there are 18 plots, one plot for each provenance: six rows down the slope × three plots along the ridgeline. Four seedlings were planted in each plot. Provenances were assigned randomly to the plots within each block. Seedlings were planted 2.5 m apart in each row, and rows were 4 m apart. Two rows of seedlings were planted as a buffer around the experimental blocks. Three blocks were sprayed with insecticide, and three others were left unsprayed. Spraying allowed estimation of potential growth rate in the absence of damage. Treatments (spraying / no spraying) were randomly assigned to each block. At the time of planting, height of seedlings ranged from 14 to 51 cm (mean = 34 cm, SD = 7 cm, $n = 432$).

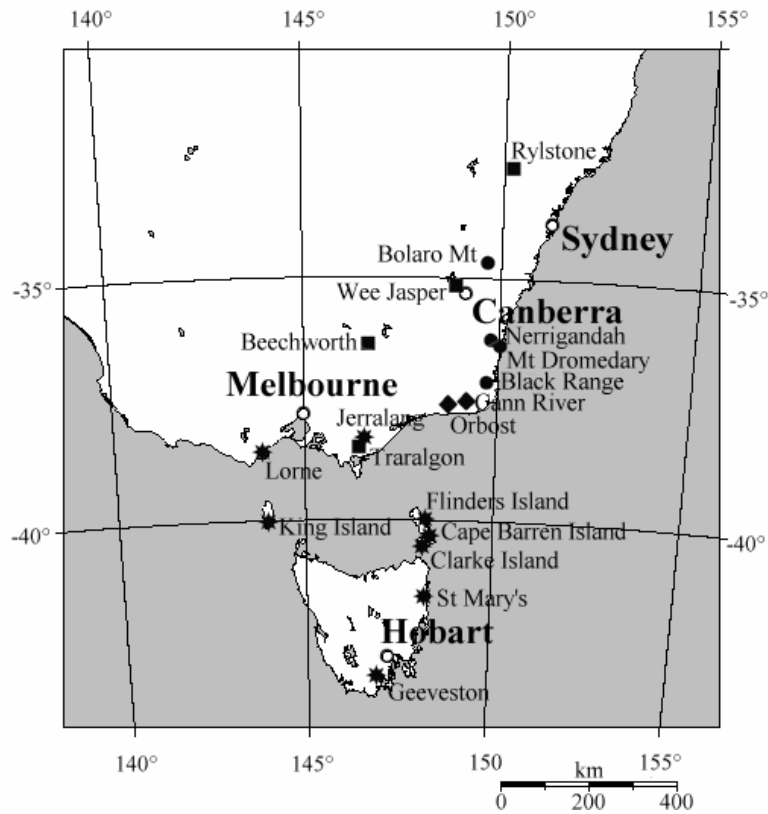


Figure 5.1 Map showing locations of 18 provenances of *E. globulus* used in this study. (Key to *Eucalyptus* subspecies: *E. g. bicostata* ■, *E. g. globulus* ★, *E. g. maidenii* ● and *E. g. pseudoglobulus* ◆).

Height and diameter at breast height (DBH) of each plant were measured at the time of planting (May 1994), June 1995, February 1996, August 1996, September 1997, September 1998, and September 1999. Initially tree height was measured to the nearest 0.1 m using graduated height poles. As the plantations developed this became impractical and the poles were replaced with an electronic measuring device (VERTEX). The standard measure of tree girth was diameter at breast height (DBH) which is defined as the diameter at 1.3 m above ground level. However, was only practical when trees were at least 2–2.5 m tall. As we were interested in detecting long term impacts of insect damage on young trees it was necessary to measure tree diameter at least annually from the time the trees were planted. When trees were too small for DBH measurements, diameter at ground level (DGL) was used as an alternative. Individual tree volume (V in cm^3) was calculated using the conical volume equation:

$$V = \frac{(DBH / 2)^2 \times Ht \times \pi}{3 \times 10^3}$$

where Ht = height in cm and DBH is diameter at breast height in cm and was square root transformed. We used plant growth rate (RGR in $\text{cm}^3 \text{cm}^{-3} \text{yr}^{-1}$) corrected for the initial plant size: which was calculated as:

$$RGR = 365 \times \frac{V_{t+1} - V_t}{V_t \times (t_{+1} - t)}$$

where V_t and V_{t+1} = square root transformed volume at time t and t_{+1} respectively and t = date of initial measurement and t_{+1} = date of final measurement. Plant volume was square root transformed.

The extent of insect damage was visually assessed at least every six months starting June 1995. Damage assessments were scheduled so as to quantify herbivory before, during, and after peak periods of herbivory by *Anoplognathus* spp. (December – January) and *M. privata* (March – August). Damage by each insect species was recorded separately. All damage assessments were conducted by the same observers for consistency. Damage by each species was scored as percentages on a scale from 0–100% in 10% intervals between 10% and 90%, with finer graduations near 0% and 100% (0%, 1%, 5% and 95%, 99%). Separately assessing damage by different insect species was possible because each insect species produced characteristic damage.

Statistical analysis

Between population analysis

Plants on the top of the ridge grew slower than those down the slope. Therefore, we first examined effects of plant location using restricted maximum likelihood analysis (REML: (Corbeil and Searle 1976)). Location of plants, specified by block, row, plot, and tree position, was used as the random effect, and insecticide treatment and population were treated as the fixed effects. Plant growth was significantly affected by location, especially that specified by row and row $\times$ block. Therefore, we estimated mean growth rates of plants for each population using REML. We used initial volume as the covariate to adjust for difference in plant size. Significance was tested using a likelihood ratio test based on the difference (Δdev) between log-likelihoods calculated for a full model, which included all terms, and a nested sub model from which the terms of interest were dropped (Genstat 5 Committee 1993). Insect damage was, however, not affected by the location of plants, and therefore, we used analysis of variance (ANOVA) to estimate mean damage for each population.

Within population analysis

For the analysis at the level of individuals within each population, we used residuals from trend surface regressions (Legendre 1990; Legendre 1993) with the plant growth as the response variable and row, block, and row $\times$ block as explanatory variables. The residuals from the trend surface regressions represent variation in plant growth rates associated with factors other than the physical location of plants within the experimental site.

We examined the relative importance of acute damage and chronic damage by estimating components of variation in plant growth due to these two types of damage. Components of variation in plant growth were estimated using a method described in Legendre (1993). The R^2 term of a multiple regression with plant growth as the response variable and both acute damage and chronic damage as explanatory variables (R^2_a) indicates combined effects of acute damage (xb), chronic damage (c), and the interaction between the acute damage and chronic damage (xb $\times$ c). Similarly, the R^2 term of a regression with just acute damage as the explanatory variable (R^2_{xb}) indicates combined effects of xb and xb $\times$ c, and the R^2 term of a regression with just chronic damage as the explanatory variable (R^2_c) indicates combined effects of c and xb $\times$ c. We estimated the component of variation in tree growth due to acute damage as ($R^2_a - R^2_c$), that due to chronic damage as ($R^2_a - R^2_{xb}$), that of xb $\times$ c as ($R^2_c + R^2_{xb} - R^2_a$), and unexplained variation as ($1 - R^2_a$).

For detecting relationships between growth and damage, we examined (1) growth rates and damage in the same year, (2) damage in year 1 and growth rates in year 2, and (3) damage in years 1 and 2 and growth rates in year 2. All three methods resulted in a similar pattern, and we report results from the relationship between growth and damage in the same year. All statistical analyses were performed using Genstat (Genstat 5 Committee 1993) and SAS (SAS Institute 1989).

Results

Over the period of the trial all except one out of 185 plants in the unsprayed treatment suffered some Christmas beetle attack, with individual plants in some years experiencing up to 90% defoliation (Table 5.1). However, the levels of Christmas beetle damage to plants varied considerably, ranging from 0 to 88% of the total cumulative damage and from 0 to 100% of total annual damage. (Table 5.1).

Table 5.1 Summary of the amount of annual damage in the 185 unsprayed plants of *E. globulus* at Lyneham Ridge. Mean $\pm$ SD (range).

Year	Acute damage (%)	Proportion (%) of acute damage in total	
		Cumulative damage	Annual damage
1995	2 $\pm$ 5 (0–30)	1 $\pm$ 3 (0–21)	37 $\pm$ 45 (0–100)
1996	55 $\pm$ 20 (0–85)	33 $\pm$ 16 (0–88)	70 $\pm$ 26 (0–100)
1997	17 $\pm$ 13 (0–70)	9 $\pm$ 7 (0–28)	64 $\pm$ 33 (0–100)
1998	24 $\pm$ 16 (0–76)	14 $\pm$ 9 (0–54)	69 $\pm$ 28 (0–100)
1999	18 $\pm$ 17 (0–90)	9 $\pm$ 8 (0–48)	72 $\pm$ 36 (0–100)

The type and degree of damage a plant experienced in any given year tended to influence the damage it suffered in both the same and following year (Table 5.2). So trees that suffered acute damage had a slight tendency to suffer less chronic damage in the same year. Also, plants that suffered severe chronic damage in one year tended to suffer less acute damage the following year. However, plants that suffered acute damage in one year did not necessarily suffer less chronic damage in the following year. Plants that tended to suffer severe chronic damage or acute damage in one year also suffered severe chronic damage or acute damage, respectively, the following year.

Across the 18 provenances of *E. globulus* there was more than a two-fold difference in acute damage and more than four-fold differences in chronic damage (Figure 5.2). There was also considerable variation in the relative amounts of chronic and acute damage that provenances received. Some populations such as Geeveston and King Island received small amounts of both mean chronic damage and mean acute damage, while other populations such as Lorne received large amounts of mean chronic damage and mean acute damage. Still other provenances such as Traralgon and St Mary's received small amounts of one type of damage and large amounts of the other type of damage. However, the correlation between mean chronic damage and mean acute damage was not strong due to populations with intermediate amounts of mean damage (Table 5.3). Severity of chronic damage in 1996–97 was positively correlated with that in 1997–98. Also, severity of acute damage in 1997–98 was positively correlated with that in 1998–99.

Growth of *E. globulus* trees varied among provenances (Figure 5.3). There were inherent differences in growth rates among populations, indicated by differences among mean plant growth rates in sprayed plants (open bars in Figure 5.3). However, the ranking of the provenances, based on potential growth rates, changed from year to year.

Table 5.2 The relationship (correlation matrix) between annual acute damage and annual chronic damage in the 185 unsprayed plants of *E. globulus* at Lyneham Ridge from 1995–98. The letter in front of each year stands for the type of damage (a = acute and c = chronic).

	c95	c96	c97	c98	c99	a95	a96	a97	a98
c96	−0.07								
c97	−0.07	0.41							
c98	0.09	0.25	0.66						
c99	0.34	−0.03	0.01	0.21					
a95	0.24	−0.05	−0.14	−0.04	0.13				
a96	0.13	−0.05	−0.16	0.01	0.12	0.18			
a97	0.10	−0.13	−0.22	−0.12	0.02	0.07	0.24		
a98	0.13	−0.09	−0.26	−0.12	0.08	0.14	0.28	0.56	
a99	−0.02	0.13	−0.12	−0.11	−0.28	0.07	0.11	0.49	0.52

Table 5.3 Correlations between annual mean acute damage and annual mean chronic damage in 18 provenances of *E. globulus* at Lyneham Ridge. The letter in front of each year stands for the type of damage (a = acute and c = chronic).

	c95	c96	c97	c98	c99	a95	a96	a97	a98
c96	−0.17								
c97	0.07	0.90							
c98	0.19	0.58	0.67						
c99	0.06	−0.04	−0.18	0.23					
a95	0.09	−0.07	−0.07	0.48	0.44				
a96	0.20	−0.24	−0.31	−0.22	0.17	0.19			
a97	−0.19	−0.12	−0.30	−0.10	0.31	0.14	0.22		
a98	−0.26	−0.11	−0.31	0.02	0.06	0.14	0.30	0.79	
a99	−0.45	0.29	0.17	0.10	−0.29	−0.11	−0.07	0.58	0.64

For each provenance, the amount and type of damage received by an individual plant influenced its growth rate, but the effect varied between years (Figure 5.4). For example, in the Cape Barren Island population, variation in individual growth rates is strongly associated with variation in chronic damage in 1995 and 1998, but not in 1996–97, and 1999. The observed differences in the strength of associations between variation in damage and variation in growth within populations is not due to differences in variability in damage or growth because there is no large difference in coefficient of variation for damage or growth among populations and years (data not shown).

In four of the five years during this study, strong associations between variation in annual growth rates and variation in acute damage were found in populations with intermediate potential growth rates (Figure 5.5). Populations with potentially fast or slow growth rates in a given year showed hardly any association between variation in annual growth rates and variation in acute or chronic damage. A higher proportion of variation in individual growth rates tended to be associated with variation in acute damage in populations with higher mean acute damage in three of the five years (Figure 5.6). However, a higher proportion of variation in individual growth rates tended to be associated with variation in chronic damage in populations with higher mean chronic damage only in 1996 (Figure 5.7).

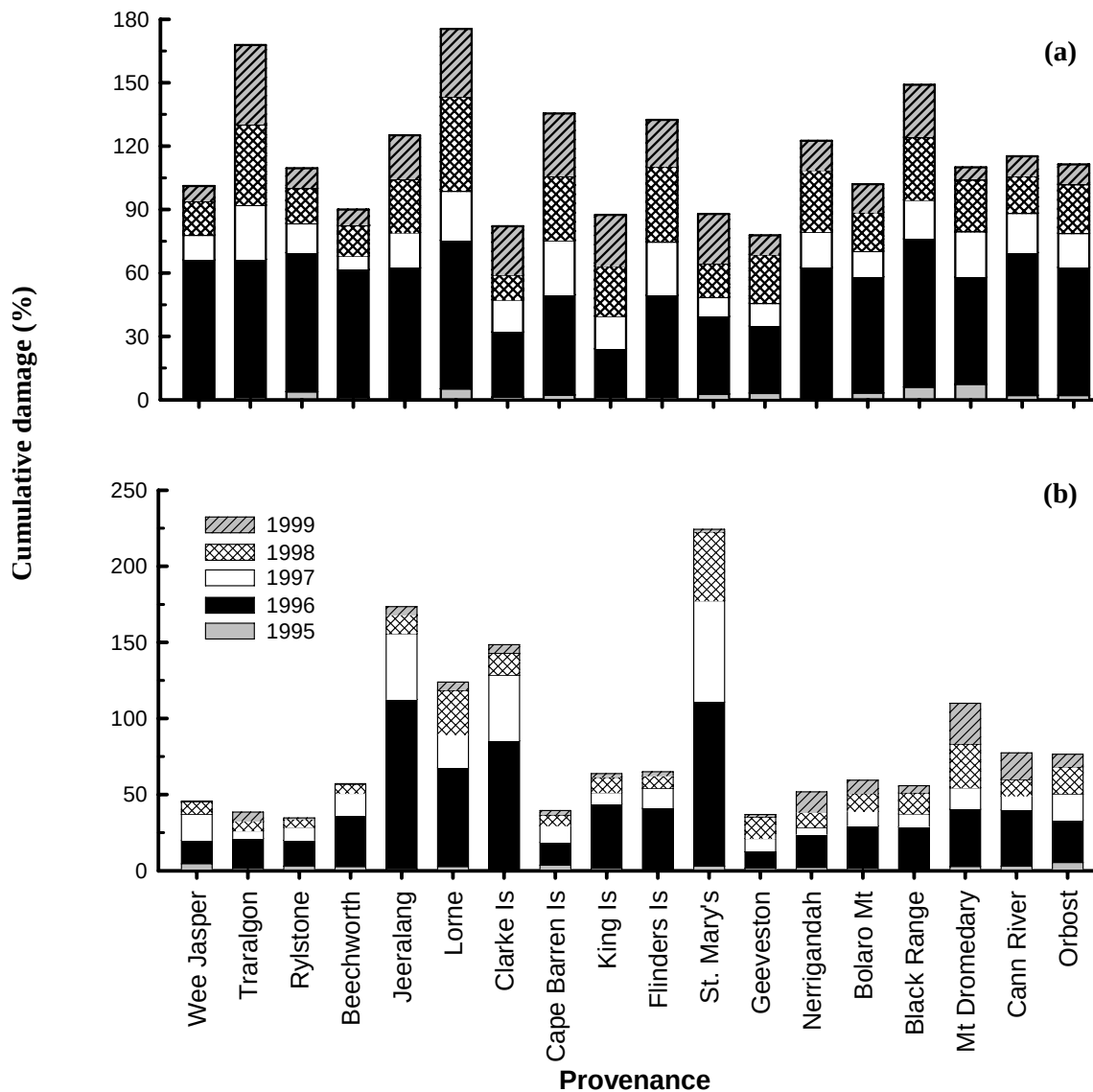


Figure 5.2 Annual acute (a) and chronic (b) damage in the 18 provenances of *E. globulus*. Annual chronic damage in some populations in 1996 exceeds 100% because damage on leaves and stems were scored separately.

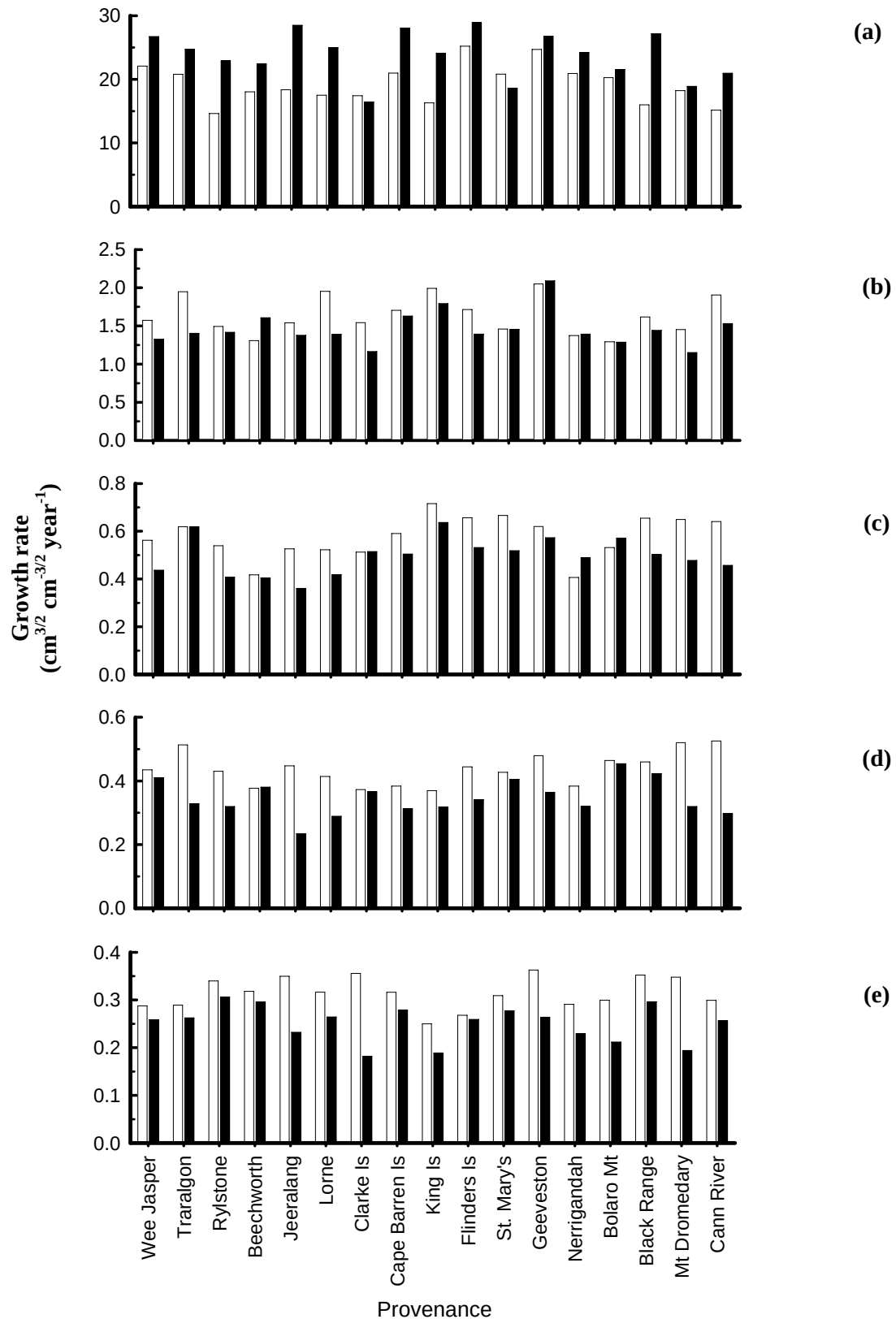


Figure 5.3 Annual growth rates of the 18 provenances of *E. globulus*. (a) 1994–95, (b) 1995–96, (c) 1996–97, (d) 1997–98, (e) 1998–99. Solid bars = growth rate of damaged plants. Open bars = growth rate of sprayed plants (potential growth rate).

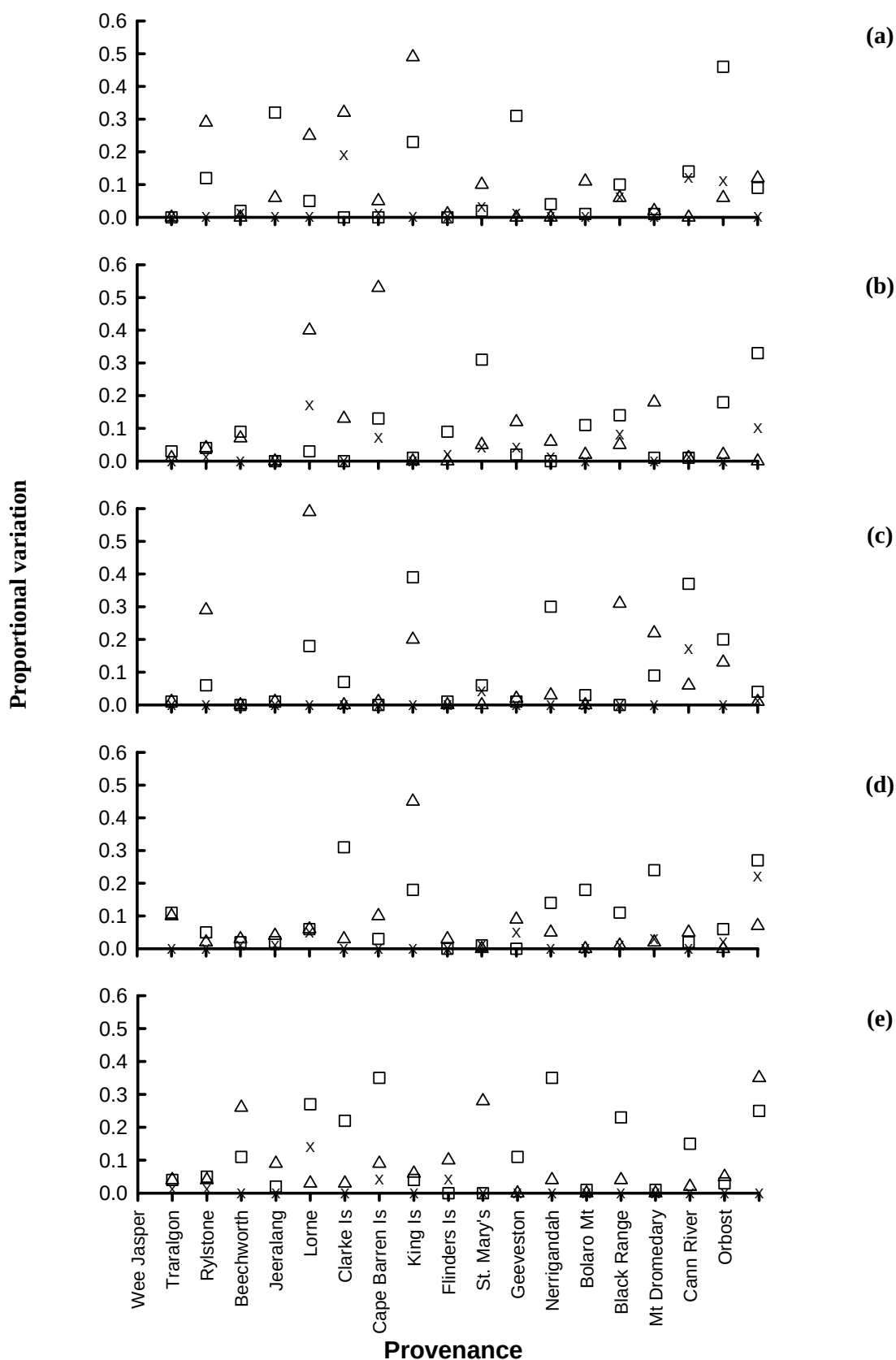


Figure 5.4 Annual change in proportion of variation in individual growth rate associated with variation in acute or chronic damage in the 18 populations of *E. globulus*. (a) 1995, (b) 1996, (c) 1997, (d) 1998 and (e) 1999. (Key: □ = association with acute damage, △ = association with chronic damage, × = association with the interaction between acute and chronic damage.)

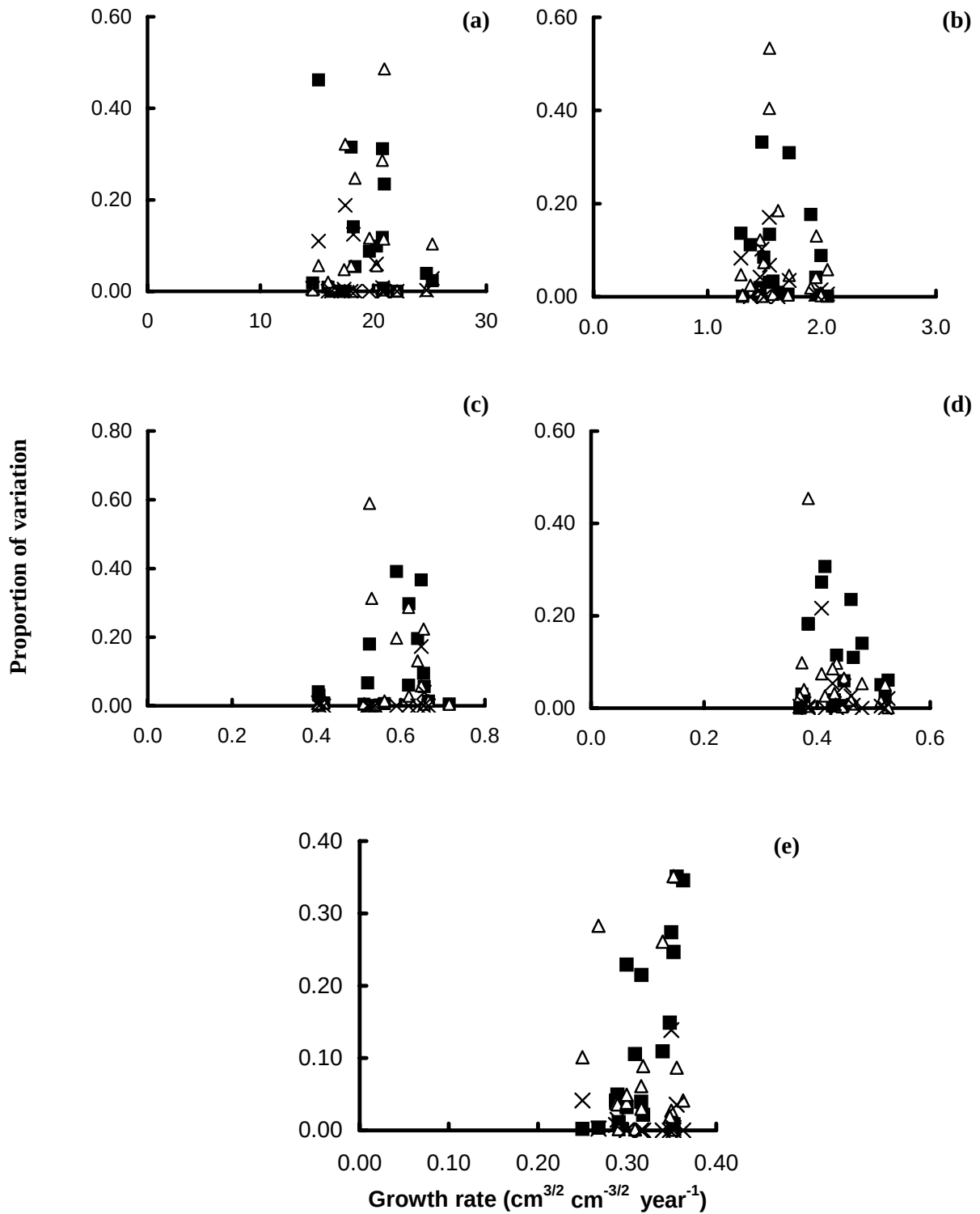


Figure 5.5 Relationships between provenance mean potential growth rates and damage-growth association among individuals within populations in (a) 1994–95, (b) 1995–96, (c) 1996–97, (d) 1997–98, (e) 1998–99. (Key: ■ = association with acute damage, △ = association with chronic damage, × = association with the interaction between acute and chronic damage.).

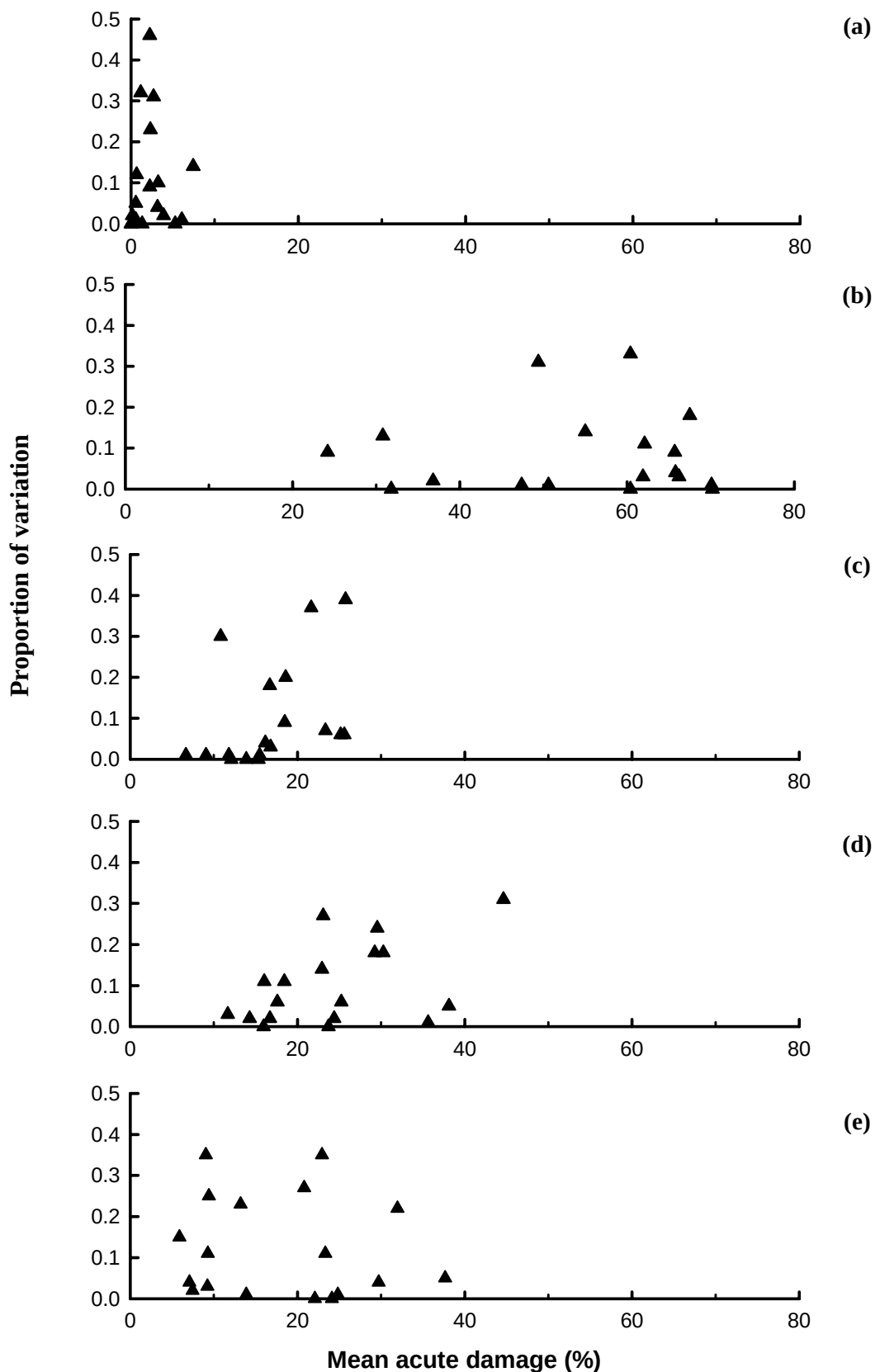


Figure 5.6 Relationships between population mean acute damage and damage-growth association among individuals within populations in (a) 1994–95, (b) 1995–96, (c) 1996–97, (d) 1997–98 and (e) 1998–99.

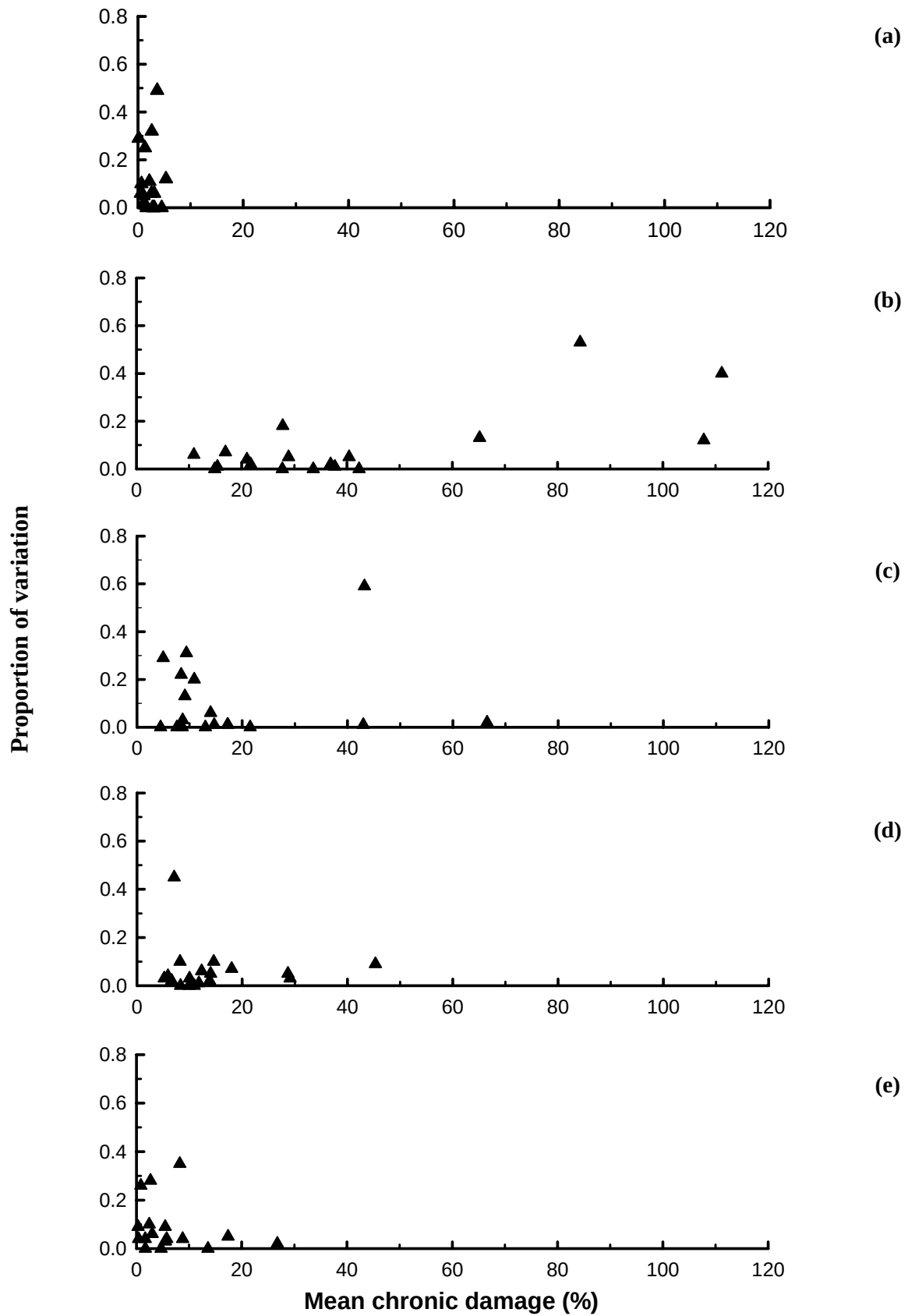


Figure 5.7 Relationships between population mean chronic damage and damage-growth association among individuals within populations in (a) 1994–95, (b) 1995–96, (c) 1996–97, (d) 1997–98 and e) 1998–99.

Discussion

We observed variation in amounts of acute and chronic damage suffered by individuals within and among 18 populations of a long lived species, *Eucalyptus globulus*. Similarly, there was variation in annual growth rates among individuals within and among the populations. Insect damage did reduce growth of *E. globulus* and the level of reduction in growth was comparable to those found in studies involving other species of *Eucalyptus* and insects (Mazanec 1968; Morrow and LaMarche Jr. 1978; Radshaw and Mazanec 1969; Stone and Bacon 1994a; Stone and Bacon 1994b; Vranjic and Gullan 1990).

Annual growth of *E. globulus* was associated with acute damage caused by *Anoplognathus* spp. in some populations with high mean acute damage. In a given population, however, there was no consistent pattern of relationship between variation in growth and variation in damage between years. This suggests that, for the levels and types of damage observed during this study, variation in growth in response to insect damage is more likely to be influenced by the environment rather than the genetic make-up of a population.

Variation in plant growth tended to be rarely associated with variation in neither acute nor chronic damage in populations when mean potential plant growth rates of those populations were high. Moreover, in populations when the potential growth rates of those populations are low, variation in plant growth tended to be hardly associated with variation in acute damage. These results suggest that insect damage affects plant growth more strongly in populations when the potential growth rates are at intermediate levels than those when the potential growth rates are very high or very low. Therefore, insect herbivores are more likely to exert strong selection pressure in populations when the potential growth rate is at intermediate levels than when the potential growth rate is very high or very low.

We observed only a few strong negative correlations between insect damage and plant growth at the level of individuals within populations. For example, many populations showed more than ten-fold difference (e.g. 5–80%) in the acute damage caused by *Anoplognathus* spp. in the summer of 1995–96, but less than 25% of variation in growth rates was associated with variation in acute damage in 16 of the 18 populations. In contrast, Marquis (1984) found reduced growth due to 30 to 100% removal of leaf area in small and medium sized plants of a tropical shrub (*Piper arieianum* C. DC.) compared with plants receiving 0 to 10% removal of leaf area. The range of damage observed in this study is comparable to that imposed by Marquis.

A possible explanation for the rarity of direct relationships between damage and growth in this study is the contribution of genetic variation to both potential growth rates and responses of plants to damage. We used seeds from a mixture of parent trees in each population. Therefore, variation in growth rates of unsprayed plants is probably a result of at least (1) variation due to potential growth rates and (2) variation in damage.

Another possible explanation is that at least some populations of *E. globulus* have evolved to tolerate insect damage and other causes of stress. The highest insect damage observed in *P. arieianum* was 50% (mean = 16.7%, SD = 8.8%) (Marquis 1984). Although there are no specific examples involving natural stands of *E. globulus*, there are many records of complete defoliation of *Eucalyptus* stands by various insects (review by Ohmart and Edwards 1991). Therefore, even 30% damage on a *P. arieianum* plant may have more substantial impact than 50% damage on an *E. globulus* plant because of the possible difference in amounts of damage frequently encountered during their evolutionary history. Moreover, many *Eucalyptus* species are thought to have evolved to withstand severe environmental stress such as fire and severe drought.

The timing of defoliation and kinds of leaves lost to herbivores may also play important roles in determining effects of defoliation on growth and sometimes survival of plants. *Anoplognathus* spp. typically avoids feeding on expanding leaves, and *E. globulus* produce new leaves in summer to autumn. Thus, even after defoliation by *Anoplognathus* spp. in mid summer, *E. globulus* trees are able

to produce new leaves. If *Anoplognathus* spp. feed also on expanding leaves or if defoliation by *Anoplognathus* spp. occurred in late autumn to early winter, then effects of defoliation may be greater than those observed in this study.

Although there was relatively minor damage by *Mnesampela privata*, this species sometimes causes major damage to *E. globulus*. Unlike *Anoplognathus* spp., *M. privata* feeds on leaves of young plants that are morphologically and chemically different from leaves of older plants. Moreover, *M. privata* larvae cause damage for a much longer time (from late summer to mid winter) than *Anoplognathus* spp. The combination of these traits sometimes results in death of young *E. globulus* plants in plantations during outbreaks (R. A. Farrow, *unpublished data*).

The responses of long-lived plants to insect damage deserve more attention. In short-lived plants, one may be able to detect direct effects of damage by insects and other herbivores on growth and reproduction of plants and consequent evolutionary changes in plant traits such as inherent growth rate, chemical defence, and tolerance. In contrast, it is more time consuming, and perhaps more difficult, to detect direct effects of the damage on growth and reproduction of long-lived plants and evolutionary changes in the plant traits. Both short-lived and long-lived plants need to be studied before making generalisations about effects of damage on plant growth. Results of this study suggests that, if insect damage was to have effects on plant growth, reproduction and consequent evolutionary change, a very severe or repeated very severe acute damage might have stronger effects than mild chronic damage repeated over the life time of plants. However, we did not have a chance to examine all different types of insect damage (e.g. severe chronic damage), and further studies are needed.

Acknowledgments

We thank J. Dowse and R. Sutherland for fieldwork, R. Cunningham and C. Donnelly for advice on REML, M. M. Court for technical assistance, and S. Strauss for comments on the manuscript. The site for the plantation experiment was provided by the ACT Forests. Financial support was provided by the Joint Venture Agroforestry Program.

6 Biology and phenology of major pests of plantation *Eucalyptus* spp. in the Murray Valley

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Summary

Aspects of the biology and ecology of those insect species that were major pests of plantation *Eucalyptus* spp. in the Murray Valley during this study are reported. Additionally what is known of these species from the scientific literature is reviewed.

The major pest species encountered in these trials were autumn gum moth, *Mnesampela privata* (Guenée). (Lepidoptera: Geometridae), brown lace lerp, *Cardiaspina fiscella* Taylor (Hemiptera: Psylloidea) and Christmas beetles, *Anoplognathus* spp. (Coleoptera: Scarabaeidae). A fourth insect pest, leafblister sawfly *Phylacteophaga* spp. (Hymenoptera: Pergidae), occasionally threatened to cause substantial damage, but heavy infestations failed to develop.

Autumn gum moth oviposition patterns and how they relate to levels of plant damage were studied at two sites. Egg batch density was found to be an unreliable predictor of subsequent damage levels. At one site (Lyneham Ridge) no relationship between egg batch density and autumn gum moth damage was found. However, at a second site (Mildura) in two of three years a strong correlation was found between egg batch density and final damage levels. Analysis of outbreak populations of autumn gum moth on a secondary host, *E. grandis*, identified processes by which moth numbers increase and possible silvicultural mechanisms to reduce the chance of outbreaks occurring are discussed.

The build up and decline from 1996 to 1999 of a brown lace lerp population on *E. grandis* at Shepparton was examined. Brown lace lerp has 3–5 generations a year. Highest population densities were found during the spring generation with the largest egg densities in November and December. Correspondingly, leaf necrosis tended to be highest in spring. Population density declined through the summer months, as did necrosis levels. Necrosis reached a low in autumn before increasing again through late winter as lerp numbers increased.

At least seven species of Christmas beetles were regularly found at or around the Lyneham Ridge site. Beetles normally occurred from December to February, although in some years were recorded as early as October and as late as March. Damage levels were correlated with the duration of beetle activity. Highest damage levels were observed when beetles were active from December to March and the lowest when beetles were active for just one month.

Introduction

The term 'pest' is entirely anthropocentric and subjective. There is no gene or group of genes for 'pestiness'. Organisms considered as pests are simply carrying out ecological activity that we perceive as impinging detrimentally on a resource of human value. All the pest is doing is competing with us, as it would with any other competitor, for a limited resource (Speight *et al.* 1999). Even the notation of detrimental impact is not absolute. One person's pest may be another's salvation. An example is *Echium plantagineum* L. (Boraginaceae), a plant originally from the Mediterranean and western Europe and introduced into Australia in the 1843 (Parsons and Cuthbertson 1992). In Victoria and

NSW where it is known as Patterson's curse, it is listed as a noxious weed while in parts of South Australia it is referred to as Salvation Jane. There are no improved pastures in the northern semi-arid regions of South Australia and the plant is valued by the sheep industry as important fodder. Additionally apiarists in the state consider it an important source of nectar because it flowers when other sources of nectar are scarce.

When insect pests are mentioned many people immediately think of outbreak species like the Australian plague locust, *Chortoicetus terminifera* (Walker) (Orthoptera: Acrididae), where damage is a result of large eruptive outbreaks. However, not all insect pests cause damage because of the sheer weight of their numbers and not all outbreaks of pest species cause economic damage. For example, insects that are disease vectors may not be tolerated even at quite low population densities. In the apple industry even one small larva of the codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), may be too many if the fruit is destined for sale in a supermarket. In forestry, depending on the final product, regular defoliation by a range of insects may be tolerated. This raises issues of damage thresholds and the economic impact of damage.

Insects compete with humans on many levels. They compete for the crops we grow to feed ourselves as well as the livelihood we try to make from all forms of production such as agriculture, horticulture and forestry. They also can spread disease to our crops, animals and us. Without some form of management, insects would cause unacceptable and enormous losses in production and health the world over. What makes an insect species a pest is usually the result of the interaction of a combination of factors. These include the insect's population dynamics, the relationship of the insect to the item being damaged (e.g. host-plant relationships in herbivores, host-vector-disease relationships in disease transmission), and abiotic factors such as climate and local weather cycles. An effective pest management strategy needs to bring all these factors together along with pesticides and cultural practices to reduce insect damage while causing minimal harm to the environment. The older concept of pest control where the focus was solely on reducing damage is now considered simplistic and ineffective. Modern pest management is more concerned with preventing outbreaks where possible and chemical control, while still important, only comes into play when prevention fails (Speight *et al.* 1999).

The key to modern pest management is the concept of integrated pest management (IPM). IPM brings together all the appropriate individual techniques and tactics for pest control for a given problem and combines them into an ecological sound and economically viable package (Speight *et al.* 1999). There are many definitions of IPM. In a recent review, Kogan (1998) defined IPM as a decision support system for the selection of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit that take into account the interests of and impacts on producers, society and the environment'. Most definitions stress the point that successful IPM needs detailed information about the pest's biology and ecology, as well as how it interacts with the environment, its natural enemies and the resource being harmed.

Understanding why and how insects reach levels where they become pests is of fundamental importance in preventing or managing damage. Knowing why a pest species abundance increases may allow strategies to be developed that prevent such increases occurring, or failing that, allow the level of damage to be reduced or contained. One common thread that links many of the factors that contribute to pest outbreaks is the provision of a large quantity of high quality food and/or breeding sites for herbivorous insects (Speight 1997). Intensive production systems whether they are agriculture, horticulture or forestry, almost invariably represent a large-scale departure from the natural habitats in which pest species evolved. Almost as invariably this results in dislocation from the community of natural enemies, host plants and competitors with which the pest species evolved. Consequently, it is not surprising that there are changes in the ecology of the pest species in such a novel situation.

Compared to Europe and North America, relatively little is known about the ecology and biology of the pests of Australian native forest trees. This is unfortunate when large areas of land are being

planted to single species plantations of native trees. Often the individuals in these plantations are selected for characteristics other than resistance to insect attack. Such trends are moving forestry in Australia towards an intensive agricultural cropping model and with it the potential for all the associated pest problems. While many of the potentially most damaging pest species have already been recognised (Elliott *et al.* 1998), the modification and simplification of natural ecosystems to form plantations often produces outbreak pests that are rare or unimportant herbivores of the natural ecosystem.

In this chapter, we will report on the biology and ecology of the major pest species encountered while undertaking the current study. Included will be a review of what is known from the scientific literature as well as the results of specific observations made during this study.

Material and methods

Pest species

The major pest species encountered in these trials were autumn gum moth, *Mnesampela privata* (Guenée). (Lepidoptera: Geometridae), the brown lace lerp, *Cardiaspina fiscella* Taylor (Hemiptera: Psyllloidea) and Christmas beetles, *Anoplognathus* spp. (Coleoptera: Scarabaeidae). A fourth insect pest, leafblister sawfly *Phylacteophaga* spp. (Hymenoptera: Pergidae), occasionally threatened to caused substantial damage but heavy infestations failed to develop.

General observations

The *E. grandis* trial at Shepparton and the *E. globulus* trial at Lyneham Ridge were observed at regular intervals. Observations at Shepparton were made at approximately two monthly intervals while at Lyneham Ridge observation frequency was adjusted to match insect activity. During periods of peak insect activity, visits to Lyneham Ridge were made at one to two week intervals, while at other times visits were made at one to two month intervals. At each visit, the species, development stage, abundance and damage of each major insect pest were recorded. In addition, pest outbreaks at other trial sites were monitored as appropriate. Where pest numbers or damage levels warranted it, more detailed sample and monitoring programs were undertaken. Details of these are given in the following section.

Specific observations

Autumn gum moth (Mnesampela privata)

From 1995 onwards, regular surveys of autumn gum moth oviposition were carried out at Lyneham Ridge. Surveys began in March each year and continued until oviposition ceased. Survey trees were divided into several strata based on height (<1 m, 1–1.5 m and > 1.5 m) and aspect of the tree (N NE, E, SE, S, SW, W, NW). The number and estimated size of egg batches in each stratum was recorded. Egg batch sizes were categorised as <20, 20–50, 50–100, 100–200 and >200.

In 1997, permanent monitoring plots were established in 10 *E. grandis* modules at Mildura. Plots were established in modules that reasonably represented the whole plantation and consisted of either 20 or 36 trees in adjacent rows. (For more details see Chapter 2). Initially trees were sampled using the same method as at Lyneham Ridge (see above) except the tree aspect was not used. However, as autumn gum moth egg numbers increased this became too time-consuming and so the number of egg batches per tree that could be found by an observer within 30 seconds at ground level was scored.

Brown lace lerp (*Cardiaspina fiscella*)

In 1996 an outbreak of the brown lace lerp developed on *E. grandis* at Shepparton. To monitor the development of the outbreak more detailed sampling of the population was established. At each regular visit to the site, thirteen trees were randomly selected from two sprayed and two unsprayed replicates. Sprayed replicates were included to monitor the effectiveness of the insecticide treatment. From each tree, a branchlet was randomly selected and all leaves removed, stored in a plastic bag and returned to the laboratory. Each leaf was inspected and scored for percentage of necrotic leaf area, number of hatched and unhatched eggs, number and type of each developmental stage and lerp number, type and contents. The lerp is the protective shell secreted by the insect.

Results and discussion

Autumn gum moth (*Mnesampela privata*)

General biology

The biology of autumn gum moth has been described by Elliott and Bashford (1978) and de Little (1981). The preferred hosts of larvae are the leaves of a group of eucalypts known as the blue gum group (Section Maidenaria) which have a distinct juvenile leaf stage. Eucalypts produce four leaf types—seedling, juvenile, intermediate and mature. In species of the blue gum group, the juvenile leaves are morphologically distinct from intermediate and mature leaves. They are oval-shaped, blue-greenish, glaucous and soft in texture whereas adult leaves are long and narrow, dark green and firm to hard in texture. The Maidenaria includes important plantation species such as the *E. globulus* Labill. species complex (including all subspecies: *E. g. bicostata* (Maiden, Blakely & J.Simm.) Kirkpatr. *E. g. globulus*, *E. g. maidenii* (F.Muell) Kirkpatr., *E. g. pseudoglobulus* (Naudin ex Maiden) Kirkpatr.) and *E. nitens* (Deane and Maiden) Maiden. The *E. globulus* species complex is particularly susceptible to attack.

Larvae are gregarious. After hatching the early instar larvae remain in a cluster on the leaf surface, skeletonising the leaves. They attempt to evade natural enemies by dropping from the leaf on silken threads. This technique is also used to aid movement around and between plants. Older third instar larvae start to make shelters by pulling leaves at branch tips together and attaching them with silk threads. Larvae remain in leaf shelters during the day and come out at night to feed. Unlike the early instars, they consume entire leaves except for the midrib and the thicker veins. As foliage is consumed, the larvae disperse onto older foliage through out the plant making new shelters as needed. The number of individuals found in the leaf shelters decreases as the larvae grow. If all the leaves on a tree are eaten the larvae can descend to the ground and crawl to a new food source. However, in plantations where tree density is high, the interlocking branches of adjacent trees usually facilitate movement between suitable hosts.

Autumn gum moth is widely distributed in farmland and woodland throughout south east and south west Australia where it is found on hosts such as apple box (*E. bridgesiana* R.Baker), candlebark (*E. rubida* Deane & Maiden) and yellow gum (*E. leucoxylon* F.Muell.). In these environments, it appears to be less common on commercial species such as *E. globulus*. Originally thought to be restricted to areas of rainfall greater than 600mm, it now also appears to be present in more arid areas wherever suitable hosts are planted.

Phenology

In south-eastern Australia autumn gum moth has one generation per year. Oviposition generally occurs in autumn from March to May. Eggs are laid onto either surface of leaves in compact groups or batches. Schumacher (1997) studied the relationship between autumn gum moth egg development and temperature using material collected from Crookwell, NSW. For the temperature range studied (10°C–

20°C), the number of day-degrees for development was $172 \pm 7^\circ\text{C-day}$ with a development threshold temperature estimated as $5.5 \pm 0.46^\circ\text{C}$. Most larvae complete development by July, but late instar larvae may be found through until September. Pupation occurs in the soil and most adults begin emerging in February and March. Using material collected from Lyneham Ridge Schumacher (1997) found that the threshold temperature for autumn gum moth larval development was $3.9 \pm 0.45^\circ\text{C}$. The number of day degrees for larval development in the temperature range 10.5°C – 21°C was $688 \pm 25 \text{ day-}^\circ\text{C}$.

Between 1995 and 1998 autumn gum moth oviposition patterns on *E. globulus* were studied at Lyneham Ridge. Most egg batches were laid between March and early May although some egg laying continued into June in most years (Figure 6.1). In 1996 eggs batches were found as early as January (not shown in Figure 6.1) and as late as the last week of June. No larvae survived from the January egg batches. The density of egg batches and the number of trees with eggs increased from 1995 to 1997 and then declined in 1998 (Figure 6.1). By 1999 there was no juvenile foliage at the site and egg surveys stopped.

Autumn gum moth oviposition varied among provenances of *E. globulus* at Lyneham Ridge (Figure 6.2a). Oviposition was lowest on two *E. g. globulus* provenances (Jeeralang and Cape Barren Island). However, there was no geographic pattern among provenance for high oviposition rates. Egg densities were greatest on provenances from three subspecies (Lorne, *E. g. globulus*; Traralgon, *E. g. bicostata*; and Orbost, *E. g. pseudoglobulus*).

The size and location within host plants of egg batches varied between years (Figure 6.3). As the size of the egg population increased from 1995 to 1997, more eggs were laid higher in the canopy (Figure 6.3a) and the number of larger batches of eggs increased (Figure 6.3b). The distribution of egg batches within trees also varied within seasons (Figure 6.4). Except in 1998, the number of batches found lower in the canopy tended to decrease through the season until May and June (Figure 6.4). In most years the proportion of eggs laid in May and June is relatively small (e.g. 6% of the total in 1995, 4% of the total in 1996) and has little influence on the over pattern of oviposition. In 1998 the pattern of oviposition was fairly uniform through the season (Figure 6.4). There was little change in the size of egg batches laid through the 1995 season while from 1996 to 1998 the proportion of larger sized egg masses tended to increase as the season progressed (Figure 6.5).

Juvenile leaves, which are the preferred site for oviposition, are also the preferred food for the early instar larvae. As the season progresses the amount of available juvenile foliage is likely to decrease as developing larvae consume it and there will be a trade off between oviposition sites and suitable foliage for early instar larvae. As suitable foliage on the lower branches is either occupied by egg batches or consumed by larvae from egg batches oviposited earlier in the season, adult females will be forced to oviposit on higher foliage. This higher foliage is likely to be less suitable for autumn gum moth development, and egg and early instar larval mortality will tend to be higher. Since suitable oviposition sites may be more abundant early in a season, females may be able to spread their egg laying effort more evenly among sites as evidenced by fewer eggs per batch and more egg batches. As the season progresses and preferred foliage is reduced, females switch to laying larger egg batches in an effort to maximise the chance of success on a decreasing resource.

From 1997 to 1998 an outbreak of autumn gum moth developed at Mildura. In June 1997, initial estimates were made of the egg population (Tables 6.1 and 6.2). Mean egg batch size was found to be 48 eggs (Table 6.2) which is comparable to Lyneham Ridge where Schumacher (1997) reported average egg batch sizes varying from 72 ± 11.6 in late March to 33 ± 5.0 in late April. All but one egg batch had hatched at the time of collection, with the last egg batch completing hatching over the collection period. Almost all (99.6%) eggs hatched successfully (Table 6.2). These data suggest that egg laying ceased about 2–3 weeks prior to assessment. The percentage of successful hatching was very high which is typical of recently colonised populations in a benign environment with little to no parasitism. Egg laying occurred on about 86% of all trees with about 35% having in excess of 10 egg batches (Table 6.1).

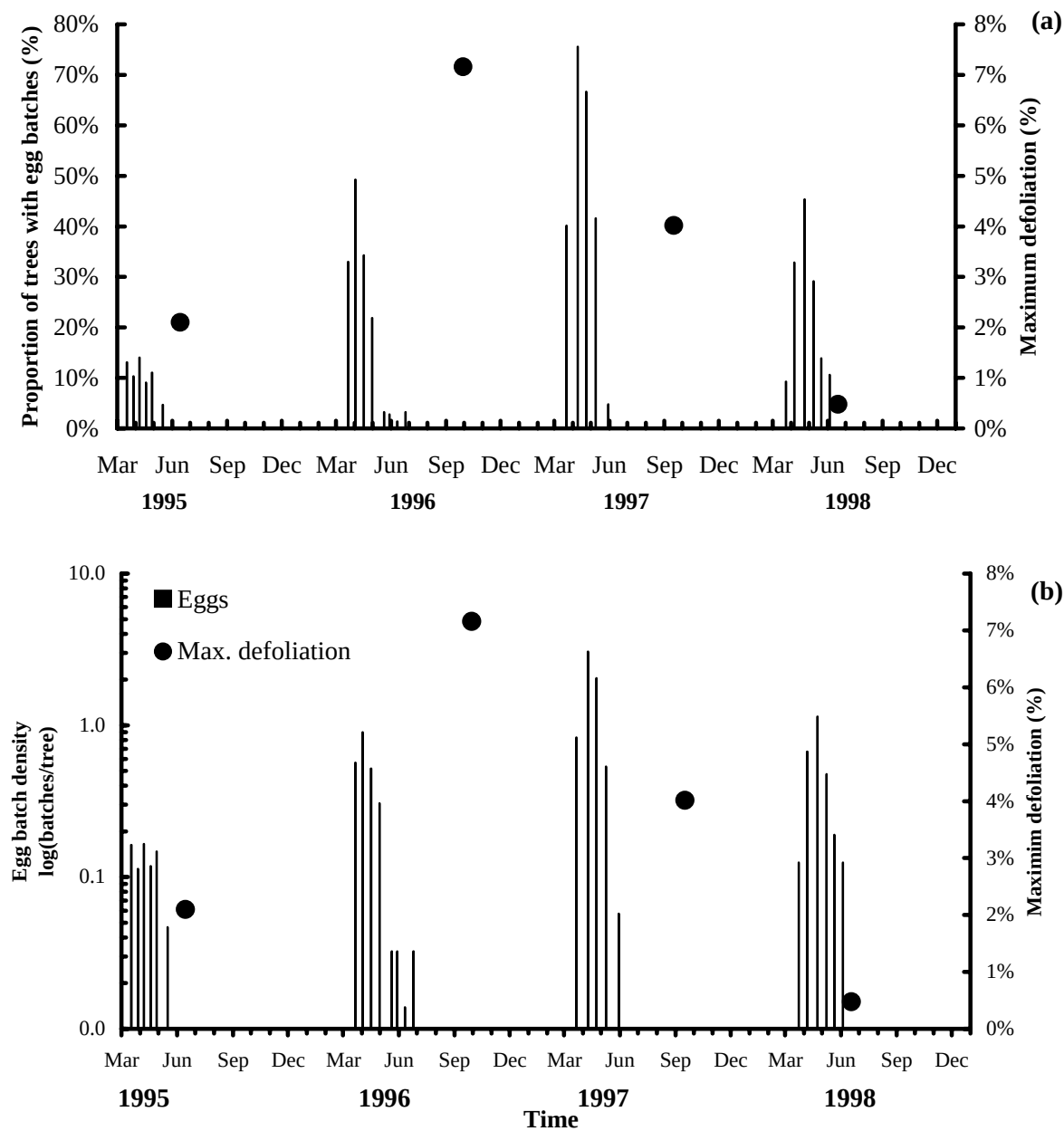


Figure 6.1 Autumn gum moth egg batches in each survey season of *E. globulus* at Lyneham Ridge. (a) Proportion of trees with egg batches. (b) Density of egg batches on trees. Maximum defoliation caused by autumn gum moth in each year is also shown.

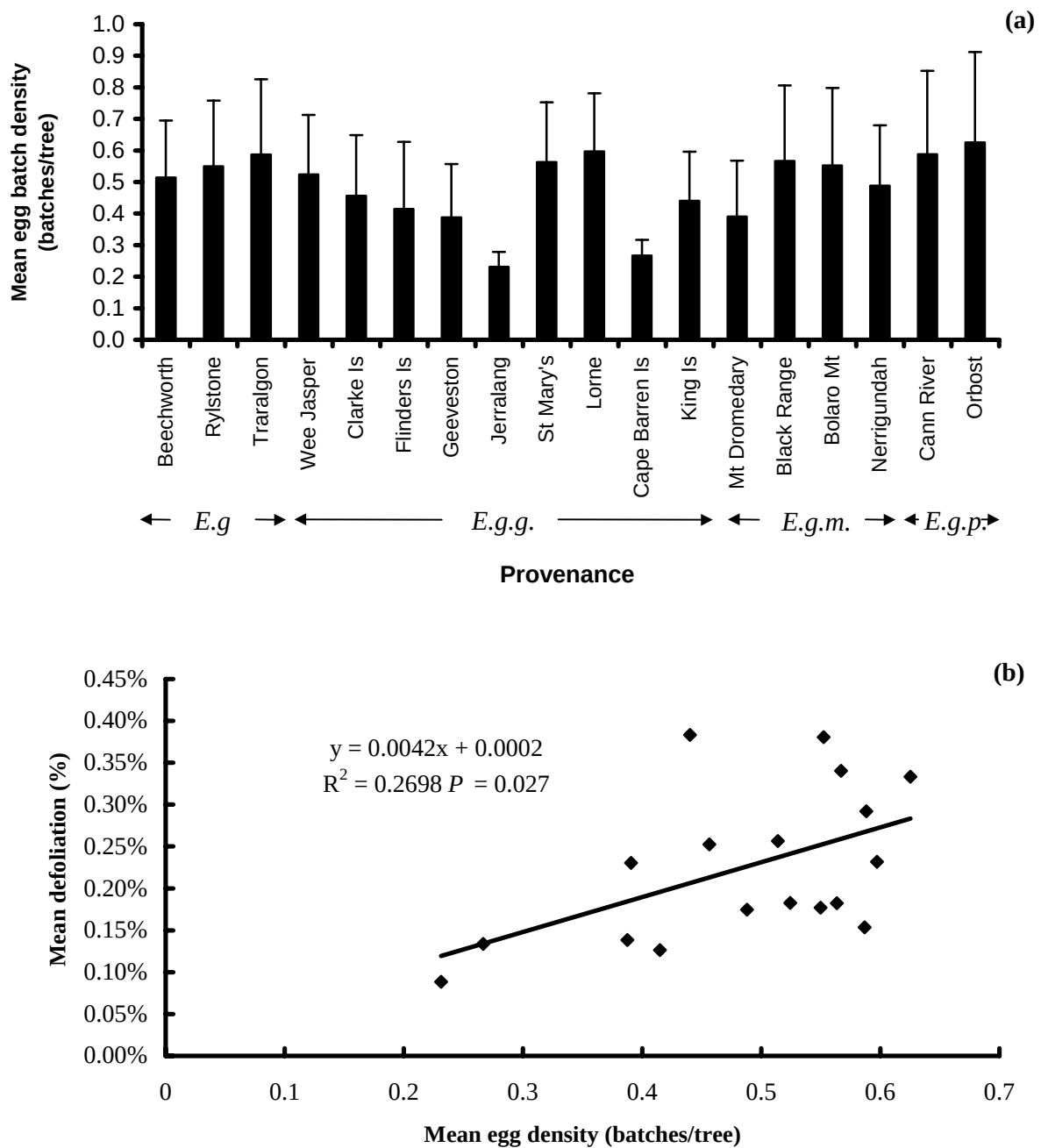


Figure 6.2 (a) Mean density of autumn gum moth egg batches on provenances of *E. globulus* at Lyneham Ridge over all years of the surveys. (Mean $\pm$ SE). and (b) Plot of the relationship between mean egg density and mean levels of defoliation for each provenance over the same period. (Key: E.g.b. = *E. g. bicostata*, E.g.g = *E. g. globulus*, E.g.m. = *E. g. maidenii*, E.g.p. = *E. g. pseudoglobulus*).

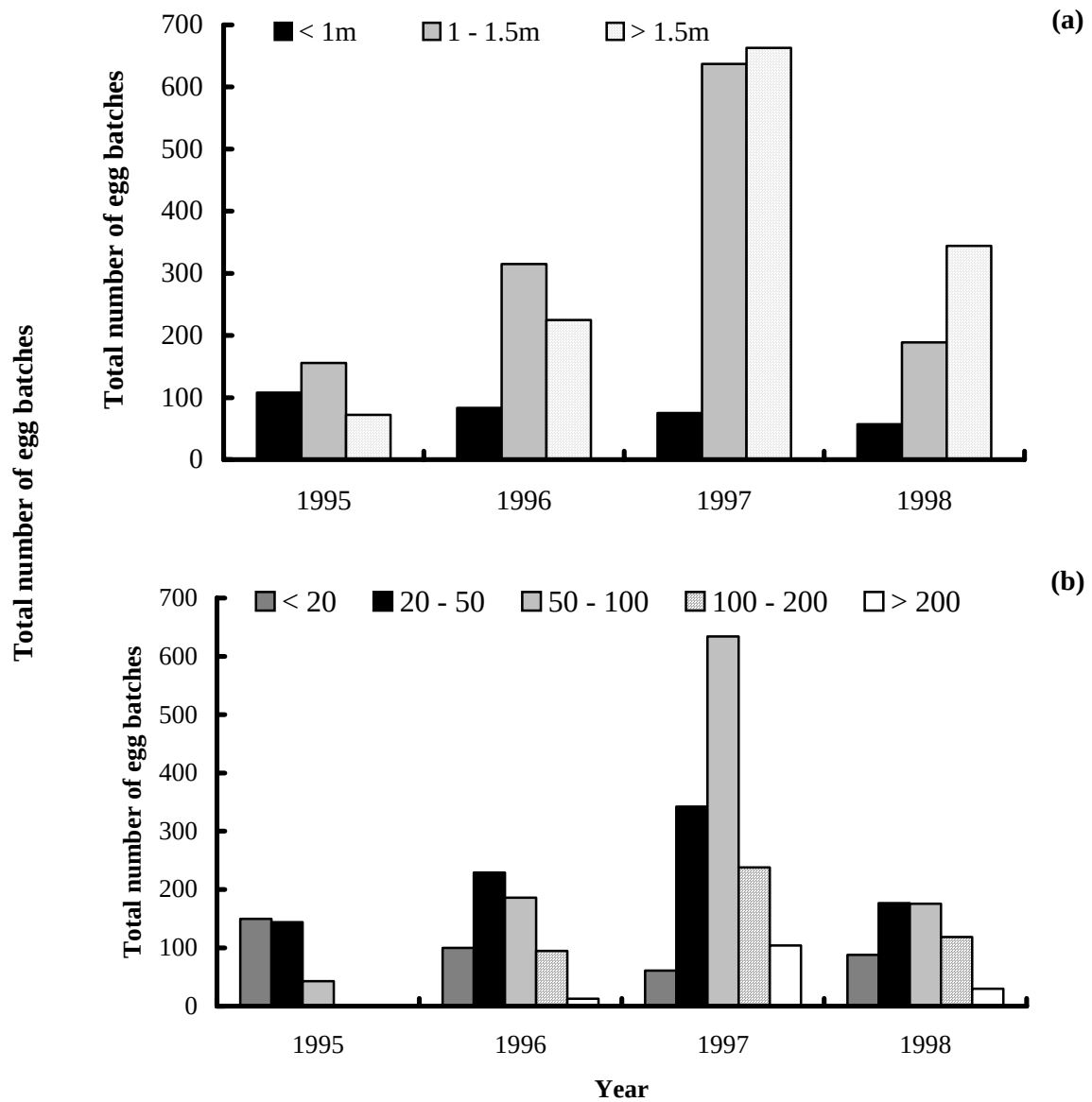


Figure 6.3 Numbers of autumn gum moth egg batches (a) at different heights and (b) of different batch sizes for each year of surveys of *E. globulus* at Lyneham Ridge.

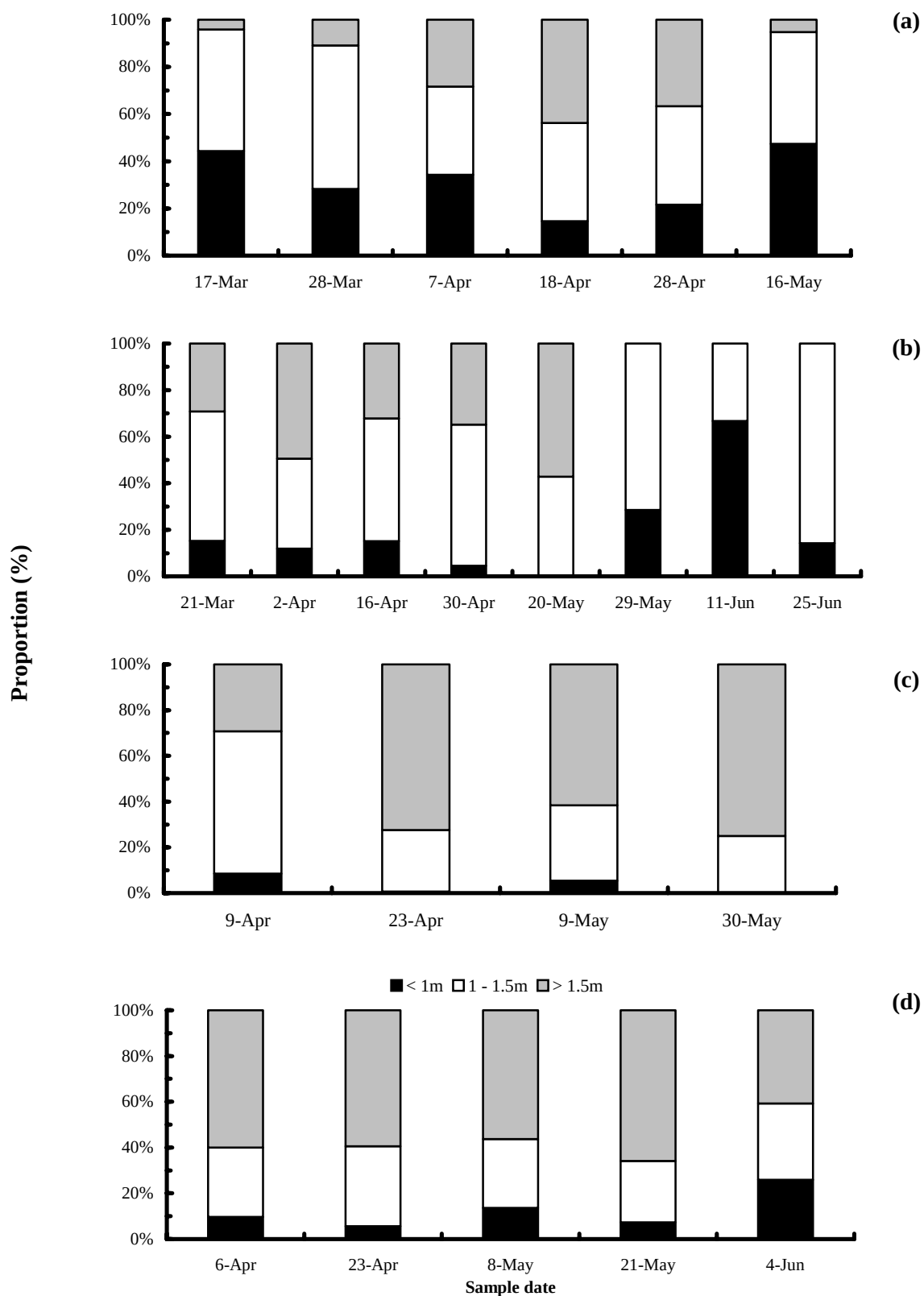


Figure 6.4 Between- and within-year variation in height above ground of autumn gum moth egg batches on *E. globulus* at Lyneham Ridge in a) 1995, b) 1996, c) 1997 and d) 1998.

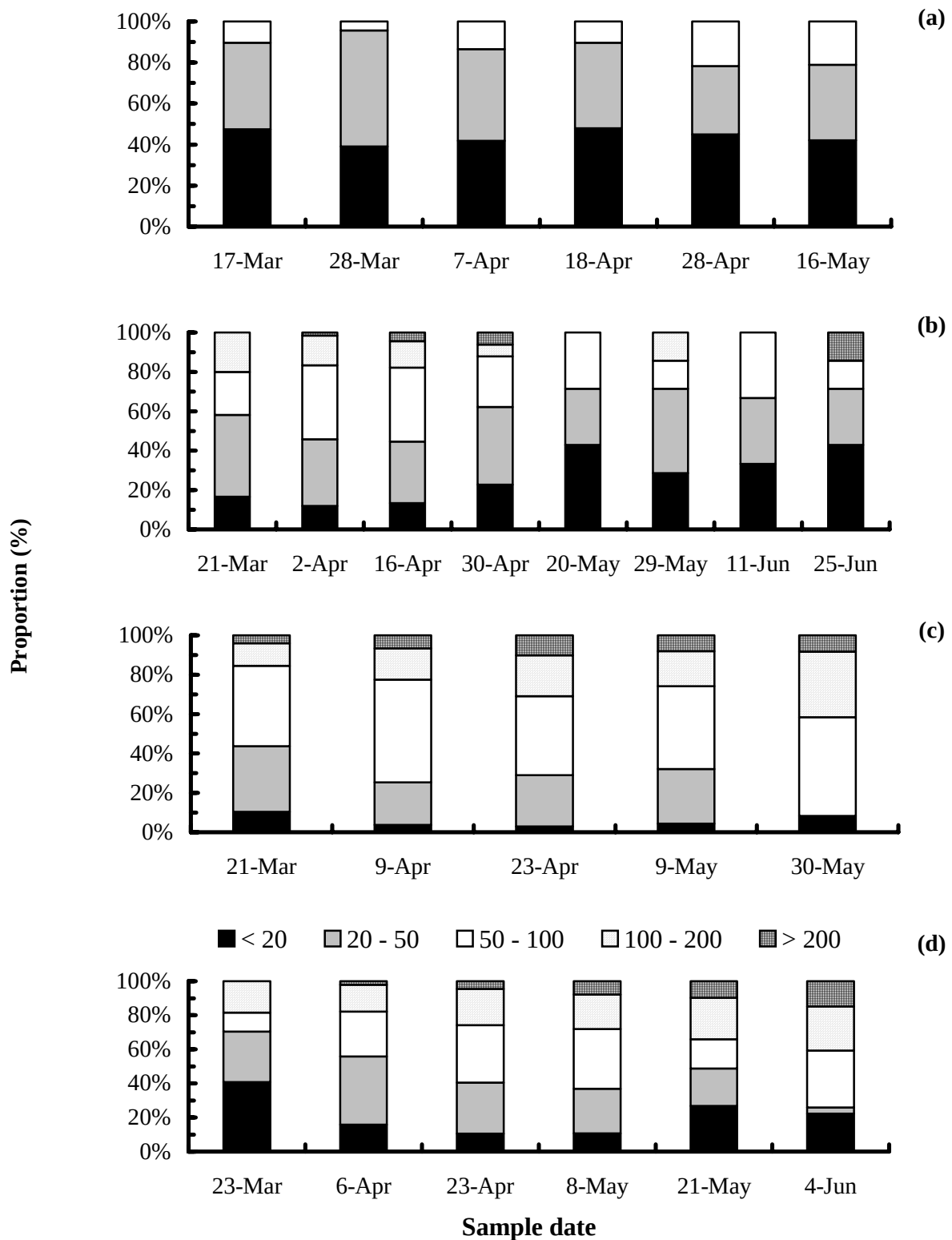


Figure 6.5 Between- and within-year variation in autumn gum moth egg batch size on *E. globulus* at Lyneham Ridge in a) 1995, b) 1996, c) 1997 and d) 1998.

Table 6.1 Density and incidence of autumn gum moth egg batches in the permanent sampling plots at Mildura in June 1997

Module	% of trees				No of trees
	0 egg batches	1–5 egg batches	6–10 egg batches	>10 egg batches	
5	30	65	5	-	20
8	-	15	-	85	20
21	3	39	36	22	36
24	35	45	20	-	20
27	11	47	25	17	36
30	30	30	25	15	20
39	-	-	30	70	20
44	25	50	25	-	20
49	-	15	35	50	20
50	-	-	5	95	20
<i>Average:</i>	13.4	30.6	20.6	35.4	

Table 6.2 Size and fate of 29 egg batches of autumn gum moth collected from Mildura in June 1997

	Unhatched and				Total
	Hatched	viable	Parasitised	Non-viable	
Total No. of eggs	1386	0.0	4	2	1392
Average batch size	47.8	0.0	0.1	0.1	48.0
Percentage	99.6%	0.0%	0.3%	0.1%	

In 1998 oviposition surveys occurred from March till May. Peak oviposition occurred in late April with 88% of trees having egg batches and an egg batch density of 13.6 egg batches per tree (Figure 6.6). This contrasts with Lyneham Ridge where over the four years the peak egg density was 3.1 egg batches per tree (Figure 6.1b). Spraying to control autumn gum moth occurred in early May 1998 and egg batch incidence and density subsequently declined (Figure 6.6). Egg batch and incidence both decreased in 1999. Peak egg batch density was about 4.2 egg batches per tree and oviposition occurred on 35% of trees (Figure 6.6).

Damage

Due to its preference for the juvenile foliage of blue gum eucalypts, autumn gum moth has been thought of as a pest of young eucalypts of the Maidenaria. However, evidence is mounting that it can equally be a pest of mature plants and of species outside of the Maidenaria. Certainly early instars feed on juvenile foliage on branches tips lower in the canopy. However, as larvae develop or as preferred leaves are consumed, more feeding occurs on mature leaves on either the inner branches or higher in the canopy. Also, if faced with a shortage of preferred feeding sites, later instar larvae may move to non-preferred or non-host species. At high population densities complete defoliation of trees can occur even when a high proportion of the leaves or trees are mature.

Examples of this type of damage were seen on an *E. grandis* plantation at Loxton, SA and Mildura, Vic in 1996 and 1998–99 respectively. *Eucalyptus grandis* is not a member of the blue gum group of eucalypts and is not considered a primary host of autumn gum moth. Although it does not have the distinct juvenile foliage of the blue gum group, juvenile leaves of *E. grandis* are noticeably softer in texture than mature foliage and a suitable feeding site for early instar larvae of autumn gum moth. Additionally the young foliage at branch tips is softer than older foliage further along the branch. The availability of soft juvenile and young foliage appears to determine the susceptibility of *E. grandis* to autumn gum moth attack. If there is sufficient soft foliage for early instar larvae of autumn gum moth to successfully develop, then the older large instars generally move into the canopy from the branch tips and feed on the tougher older leaves.

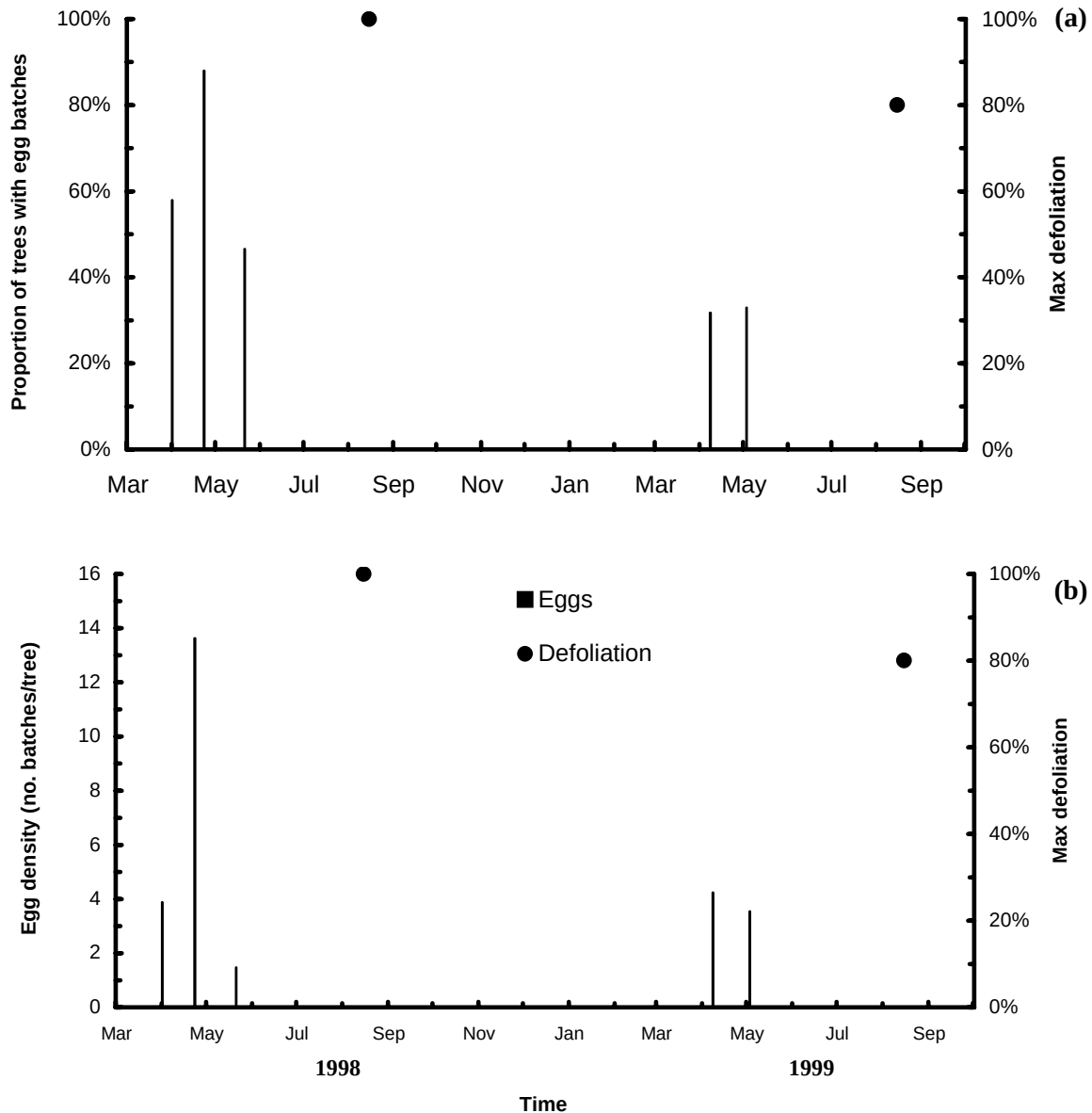


Figure 6.6 Autumn gum moth egg batches in 1998 and 1999 on *E. grandis* at Mildura. (a) Proportion of trees with egg batches. (b) Density of egg batches on trees. Also plotted is the maximum autumn gum moth defoliation for each year.

The plantation of *E. grandis* at Loxton was about 12 years old and the trees were over 30 m tall in 1996 when an outbreak population of autumn gum moth caused heavy defoliation. Heavy defoliation by autumn gum moth on mature *E. grandis* had been recorded previously. When the site was visited in July 1996, substantial defoliation of mature leaves in the crown had occurred. Two factors appeared to have contributed to this. Trees were of a sufficient height that most of the lower branches had been removed by self-pruning. However, little site maintenance had been carried out and trees along the edge of each module had many lower branches. Much of the foliage on these branches was made up of soft young leaves and had been heavily attacked by early instar larvae of autumn gum moth. Additionally, around the edge of the modules and in gaps within the modules, self-sown juvenile *E. grandis* and coppice growth had also been heavily attacked by autumn gum moth. It appears that the presence of soft foliage suitable for early instar larvae had allowed a large population of early

instar larvae to develop successfully. As larvae reached late instars, they moved up into the canopy causing severe damage to mature foliage.

At Mildura and Lyneham Ridge, a wide range of insect densities and damage levels occurred, allowing an examination of the relationship between egg density and subsequent damage. At Lyneham Ridge where autumn gum moth damage was low, no pattern was found between egg density and autumn gum moth damage within years. The maximum level of autumn gum moth defoliation and egg density increased from 1995 to 1996 (Figure 6.1b). However, although egg batch density doubled from 1996 to 1997, defoliation levels decreased. Egg density in 1998 was less than that in 1997 and autumn gum moth defoliation again decreased. There was, however, a significant, but weak relationship between mean provenance defoliation and mean provenance egg density when average over the four years of the surveys (Figure 6.2b; $P = 0.027$, $R^2 = 0.2698$). Variation among provenances in susceptibility to autumn gum moth damage has been reported previously for *E. globulus* by Farrow *et al.* (1994) who found that seedlots from Tasmania and the Bass Strait Islands were less susceptible than mainland seedlots (See also Chapter 4).

At Mildura in 1997, mean autumn gum moth damage in the two trial plots was low ($2.80\% \pm 0.28$ (0–100)), although 94% of trees had suffered some damage by the end of the feeding season. However, defoliation levels in the other permanent sample plots (Table 6.3) suggested that most modules were incurring much greater damage. Across all the permanent sampling plots there was a correlation between damage levels at the end of the feeding season (October) and the egg batch density at the end of the oviposition season (June) ($r^2 = 0.8$; Table 6.3).

Table 6.3 Relationship between peak autumn gum moth egg batch density and final level of foliage damage in the permanent sampling plots at Mildura in 1997

Module	Egg batches tree ⁻¹ on 18-Jun	% foliage damage		No of trees
		18-Jun	13-Oct	
5	1.9	0.7	1.2	20
8	17.8	4.9	25.0	20
21	9.8	17.9	50.1	36
24	3.0	0.8	1.2	20
27	7.6	5.3	4.6	36
30	6.2	0.9	1.1	20
39	17.0	10.5	31.0	20
44	4.0	1.2	2.5	20
49	14.3	10.0	44.8	20
50	19.5	33.8	60.9	20
Average:	10.1	8.6	22.2	

Field observations in 1997 suggested that the sampling plots with the highest levels of damage and egg batches were those that had the greatest level of canopy closure. This may have been due to the moths preference for sheltered conditions provided by the denser stands. Further evidence to support this hypothesis was that more egg laying occurred on the eastern than the western side of trees. Furthermore, in the stands with greater canopy closure, greatest damage was reported on the smaller trees (Figure. 6.7). This may indicate a preference for oviposition on sheltered sites or that foliage of smaller trees is more attractive. Trees with a high leaf area index (LAI) have high self-shading of leaves and these leave use up more in respiration than they produce in gross photosynthesis (Crawley 1997). It may be that this change in leaf metabolism alters the suitability of the leaf to insect attack. Regardless of tree size, most larvae and damage in 1997 was observed on the lower foliage.

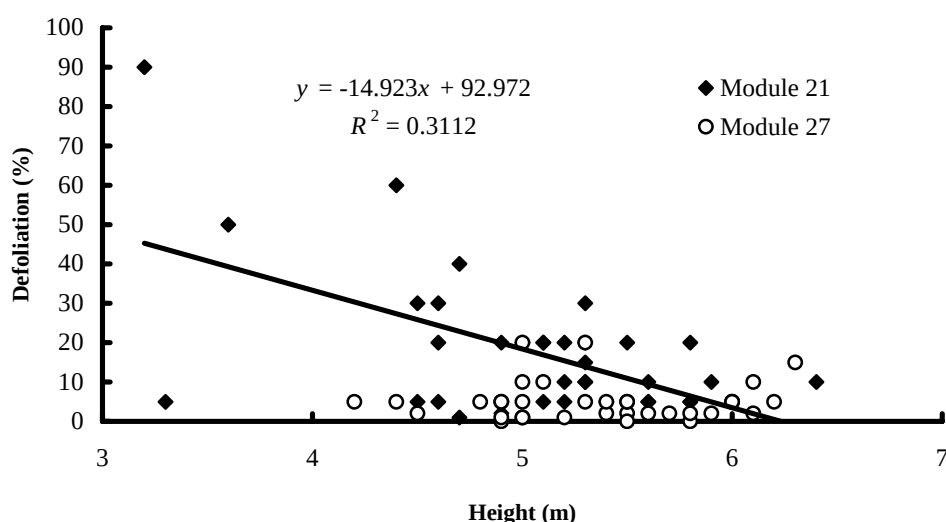


Figure 6.7 Relationship between tree height and foliage damage by autumn gum moth in the permanent sampling plots in modules 21 and 27.

In 1998, autumn gum moth egg batch density at Mildura was the largest seen at any site during the study (c.f. Figures 6.1b and 6.6b). By the end of the feeding season there was total defoliation at the two trial sites (Mildura-A = module 24 and Mildura-B = module 30) and high levels of defoliation of the remaining unsprayed modules (Table 6.4). Again, there was a strong correlation between egg batch density and final damage levels ($r^2 = 0.98$, Table 6.4).

Table 6.4 Relationship between peak autumn gum moth egg batch density and final foliage damage in the unsprayed permanent sampling plots at Mildura in 1998 and 1999

Year	Module	Egg batches /tree in April	% foliage damage		No of trees
			April	July	
1998	24	14.0	1.5	100	10
	30	13.6	1.6	100	10
	39	7.9	1.2	88	10
	44	10.2	1.2	90	20
	Average:	11.4	1.4	94.5	
1999	24	3.8	0.0	80.8	10
	30	3.0	24.0	79.3	19
	Average:	3.3	8.0	61.8	

Although egg batch density of autumn gum moth decreased greatly in 1999, damage levels did not decrease proportionally (Figure 6.6b). Only the two trial modules were left unsprayed in 1999 (Table 6.4) and there was insufficient data to determine if there was any relationship between egg density and final levels of defoliation. Spraying of the bulk of the site in 1998 and 1999 severely reduced the population of autumn gum moth. Monitoring of adult moth numbers by light trapping in late summer and early autumn 2000 indicated that autumn gum moth would not be a threat to the plantation and no surveys for eggs were carried out. This was borne out by the damage survey in August 2000, which found mean defoliation by autumn gum moth of $13.0\% \pm 0.60\%$ (0%–100%).

Autumn gum moth damage at Lyneham Ridge and Mildura represented two extremes. At Lyneham Ridge, moths were found over a number of years and although egg densities built up in some years, damage remained very low. At Mildura the population exploded from 1997 to 1998 with unsprayed

modules suffering 80% to 100% defoliation in 1998. While a relationship between egg density and damage was apparent at Mildura, things were less clear at Lyneham Ridge. There was also an interesting contrast between egg density and damage at the two sites. For example the peak egg density at Lyneham Ridge, which occurred in 1997, was 3.4 egg batches per tree, which is comparable to Mildura in 1999 with 4.2 egg batches per tree. However, mean annual damage at Lyneham Ridge in 1997 was approximately 7% while at Mildura in 1999 mean annual damage was approximately 80%. Also of interest at Mildura in 1999 is the incidence of egg batches on tree. Although only 35% of trees had egg batches, final defoliation was 80%. The low incidence and density of egg batches suggest that a comparatively small population of larvae, actively moving between trees in the modules caused the damage. This may have been due to the heavy damage in the previous year. Having been totally defoliated, the trees would have had an even aged population of young foliage that was more suitable for autumn gum moth development than mature foliage. This may have made the trees more susceptible to heavy damage by a comparatively small population of autumn gum moth.

Egg density alone was not always a reliable predictor of final damage. Factors such as natural enemies, lack of suitable feeding sites and adverse weather conditions can all cause heavy mortality to young larvae. While it would be expected that heavy defoliation by autumn gum moth be associated with high densities of eggs, high egg density alone does not predict high levels of defoliation. Because of time constraints, it was not possible to score egg batch size at Mildura to define the relationship between egg batch density and the level of damage.

Natural enemies

At Loxton, a viral epizootic caused high levels of mortality among late instar larvae of autumn gum moth. Dr Peter Christian, CSIRO Entomology, has undertaken preliminary work on isolating and characterising the pathogen. It appears that the pathogen maybe widespread in autumn gum moth populations although its abundance is normally low. It is possible that this virus could be developed into a biopesticide.

A number of egg and larval parasitoids have been recorded as being associated with autumn gum moth (de Little 1981; Elliott and Bashford 1978; Schumacher 1997). These include a scelionid egg parasite, *Telenomus* sp. (Hymenoptera: Scelionidae), several ichneumonid and braconid larval and pupal parasitoids and an unidentified species of tachinid fly.

Schumacher (1997) studied in detail the parasitoid complex of autumn gum moth at Lyneham Ridge in 1993. *Telenomus* sp. was the only egg parasitoid found and it parasitised 14% of the autumn gum moth eggs. Most eggs were not parasitised due to lack of synchronous abundance of the parasitoid. Eggs that were oviposited early in the season swamped the ability of *Telenomus* sp. to respond with higher oviposition rates and a numerical response was not possible due to the short period that eggs were available. Two parasitoids, a new species of *Glyptapanteles* (Hymenoptera: Ichneumonidae) and *Casinarina micra* Gauld (Hymenoptera: Braconidae) were found parasitising larval autumn gum moth. Both species emerged from fourth instar larvae, but only accounted for four deaths out of 426 larvae observed. About 10% of autumn gum moth pupae were parasitised by *Heteropelma scaposum* Morely (Hymenoptera: Ichneumonidae). *Heteropelma scaposum* is a common parasite of numerous Lepidoptera including the agricultural pest *Helicoverpa armigera* (Hübner) and *Spodoptera litura* F. (Lepidoptera: Noctuidae).

Brown lace lerp (*Cardiaspina fiscella*)

General biology

The brown lace lerp is one of many species of cardiaspine psyllids that feed on eucalypts, generally with a high degree of host specificity. The biology of cardiaspine psyllids is generally quite similar and Clark (1962) has described the biology of *Cardiaspina albitextura* Taylor (Hemiptera: Psylloidea)

in detail. One of the characteristics of some psyllids is the secretion of a protective shell, the characteristic lerp, by the nymph as it feeds. The lerp is made of starch derived from the plant sap, is glued to the leaf, and is enlarged from one edge as the psyllid grows.

The distribution of cardiaspine psyllids normally mirrors the natural range of their host species. However, with the planting of host trees into areas where they are not endemic, several species such as the brown lace lerp have extended their range by colonising these non-endemic plantings. This is the case at Shepparton, which was the only trial site where psyllid numbers reached levels that resulted in trees sustaining substantial damage.

Phenology

Depending on ambient conditions cardiaspine psyllids have 3–5 generations per year. Development is continuous with no resting stages although developmental rates normally slow during winter resulting in synchronised egg laying in spring. Depending on local conditions two to four generations can occur from October to April. Detailed observation of the brown lace lerp population at Shepparton began in late 1996 (Figure 6.8). An outbreak of the psyllid the previous summer had resulted in mean damage levels on trees of 50.9%.

Development of brown lace lerp at Shepparton followed the general pattern for cardiaspine psyllids. Peaks of egg laying were found in November and December of each year coinciding with development of the spring generation of psyllids (Figure 6.9). In summer eggs take about 2–3 weeks to hatch and nymphs about 3–5 weeks to develop to adults. In each year lerp density built in the period between November and February as the first summer generation developed (Figure 6.9). Normally generations of psyllids tend to rapidly succeed one another with minimal overlap. The pattern of egg density seen between February and June is consistent with the sequential development of several generations. However, peak lerp density in the subsequent summer generations declined in every year (Figure 6.9).

At low densities, psyllid populations appear to be controlled by natural enemies (Morgan 1984) and plant nutrient levels (Clark and Dallwitz 1974; Clark and Dallwitz 1975). At high density, availability of feeding sites probably limit numbers (Clark and Dallwitz 1974; Clark and Dallwitz 1975; Morgan 1984). Environmental effects, such as weather patterns, mediated through changes in plant nutrient levels may also influence psyllid numbers (Taylor 1997). The regular decrease in psyllid density during the hotter, drier summer months may be an example of this. *Eucalyptus grandis* is a subtropical species that even when well irrigated, suffers dehydration stress under conditions of low humidity (Myers *et al.* 1996). The plant responds to such stress by closing its stomata and stopping carbon dioxide uptake. It is likely that such a response to dehydration stress would have an adverse impact on psyllid growth as the production and transport of nutrients in leaves would be slowed or stopped. Another possible explanation is that the numbers of natural enemies may have increased to levels that impacted on psyllid numbers, but there was little evidence of parasitoid activity or predation in any of the samples.

In 1998–99, the summer generations of brown lace lerp failed to develop. Normal egg densities were seen in December (Figure 6.8a) and the population of first instar nymphs was high (Figure 6.8b). However, by February 1999 the population was restricted to only first instar nymphs and density was very low (0.1 nymphs / leaf). In the April and June samples of 1999, no psyllids were found. Such a sudden crash in the population was probably due to unfavourable weather conditions in January or February causing severe mortality to the early instars.

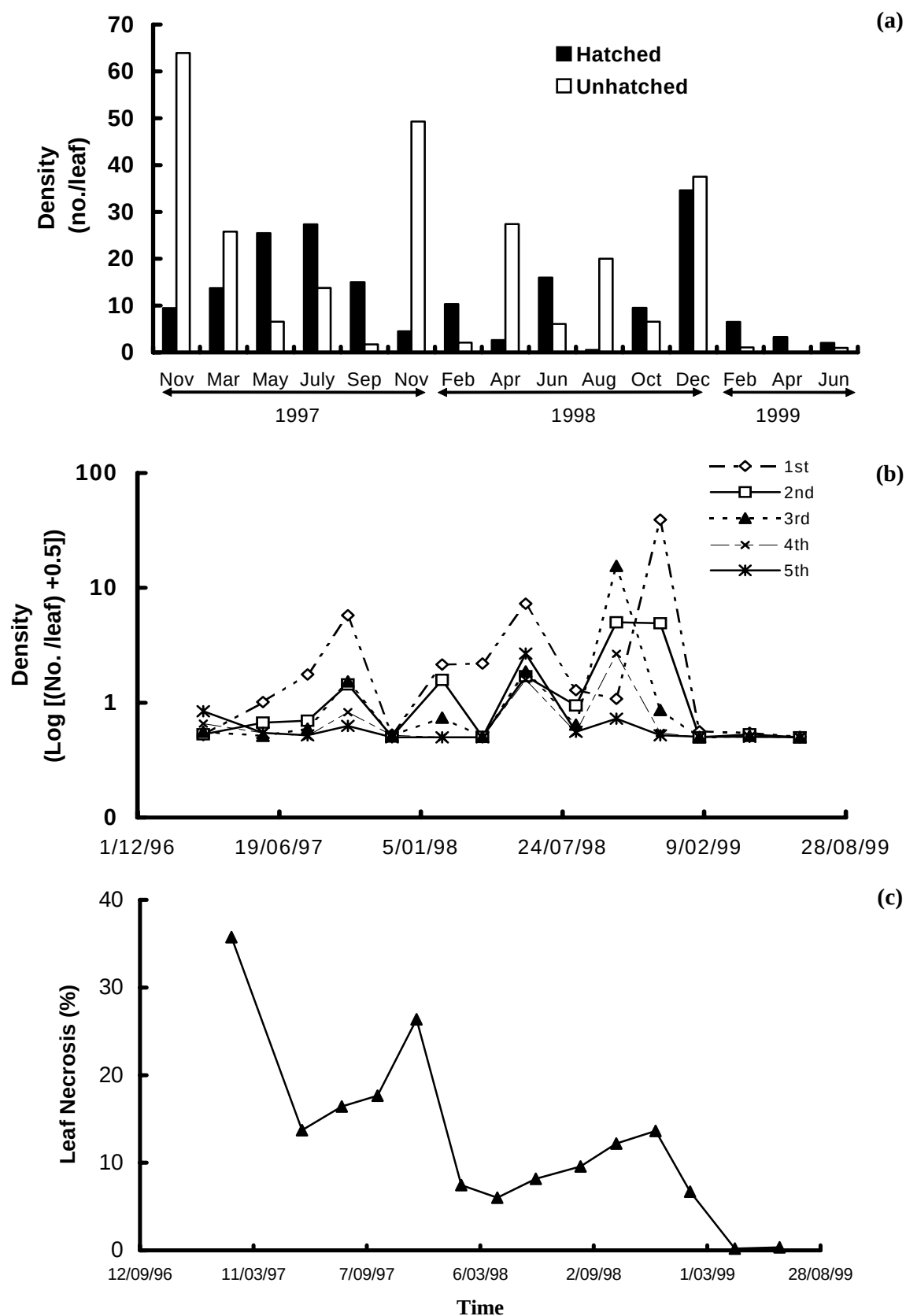


Figure 6.8 Number of *Cardiaspina fiscella* (a) eggs and (b) nymph instars/leaf and c) percentage leaf necrosis on unsprayed *E. grandis* at Shepparton.

Damage

Damage by the brown lace lerp is seen as purple patches of dead tissue (necrosis) on leaves. It spreads from the feeding sites of the nymphs and an enzyme injected into the leaf causes tissue death. Adults also feed on leaves but do not cause necrosis. In dense infestations, whole leaves may be affected, resulting in the leaf becoming non-functional and being shed prematurely. Repeated defoliation caused by prolonged outbreaks over several years can result in dieback.

At Shepparton peak damage levels decreased over time (Figure 6.8c). The greatest damage was due to the summer generations in 1996–97. The plants recovered through autumn but damage increased through winter until it peaked again in the spring of 1997. In 1998, damage remained low through the summer generations, but increased slowly over winter to a peak in late December. The psyllid population crashed over the summer of 1998–99 and by April 1999, no damage was apparent. The density of large lerps seems to best mirror damage levels (Figure 6.9c).

Christmas beetle (*Anoplognathus* spp.)

General biology

Christmas beetles are common herbivores on many *Eucalyptus* species on farmland and totally defoliate some trees in some years (Carne *et al.* 1974b; Edwards *et al.* 1993; Edwards *et al.* 1990). Eucalypts are only damaged by the feeding of adult beetles. The larvae live in soil and feed on the roots of native and introduced grass species. The adults feed by making zigzag cuts to leaves, progressively shredding the leaf material with much waste in the process. Beetles can become very abundant during a few weeks in summer and at high densities can defoliate large trees over extensive areas.

Phenology

Christmas beetles have an annual or biennial life cycle with a long larval period spent underground. Eggs are laid in early summer and there are three instars. In warmer regions, the third instar is reached by the following spring and pupation occurs near the soil surface. In cooler areas, most larvae only reach the second instar by the spring following laying and continue development for another year before pupating. In some regions and in some seasons, a mixture of 1 and 2 year life-cycles can develop. The pupal stage takes 2–3 weeks and adults emerge from the pupal cell, but wait for a fall of rain before attempting to dig their way to the surface. Adults live for only 2–3 weeks. Drought in late spring or early summer is correlated with low abundance of Christmas beetles. (Carne *et al.* 1981)

Christmas beetles are widely distributed throughout grassy woodland, agricultural grasslands (especially improved pastures) and open forests in the higher rainfall areas (> 600 mm p.a.) of south east Australia. Areas with summer rainfall maxima are especially favoured. They are less common in areas with winter dominated rainfall and in arid zones because of the larvae's inability to survive extended dry periods. Increased areas of farmland in the preferred habitat have provided favourable conditions for larvae, and a corresponding reduction in areas of woodland has resulted in high concentration of adults on a small number of farmland trees. Severe defoliation of farmland trees is considered to be due to such changes in land use (Ohmart and Edwards 1991).

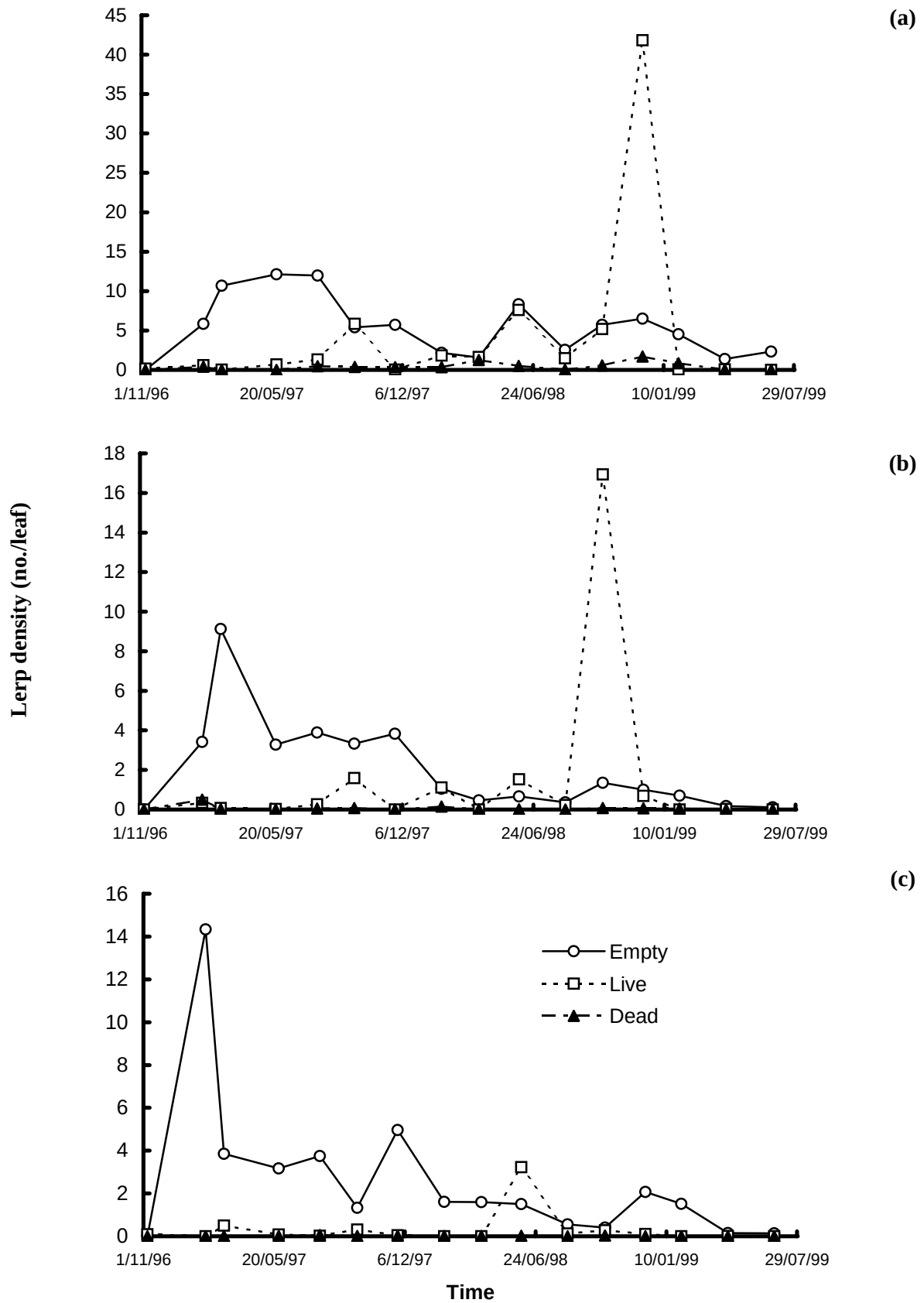


Figure 6.9 Density of the contents of different size lerp stages of the brown lace lerp on unsprayed *E. grandis* at Shepparton between 1996 and 1999. (a) Small, (b) Medium, and (c) Large lerp stages.

At least seven species of Christmas beetle have been observed at the Lyneham Ridge study site in Canberra (*A. pallidicollis* Blanchard, *A. velutinus* Boisduval, *A. chloropyrus* (Drapiez), *A. hirsutus* Burmeister, *A. montanus* Macleay, *A. suturalis* Boisduval, and *A. viriditarsis* Leach). Depending on the mix of species and life-cycle strategies, and the timing of rain, several waves of emergence and feeding activity can occur between late November and February. At Lyneham Ridge beetles occurred mostly from December to February, although in some years they were seen as early as October or as late as March (Table 6.5).

Table 6.5 Occurrence of adult Christmas beetles on *E. globulus* at Lyneham Ridge from 1995 to 1998

Month	1995	1996	1997	1998
January		X	X	X
February	X	X	X	
March		X		
April				
May				
June				
July				
August				
September				
October				X
November			X	
December	X	X	X	X

Damage

Greatest damage was found in 1995–96 (mean 55%±20% S.E.) when beetles occurred for up to four months and lowest in 1994–95 (2%±5%) when beetles occurred for less than a month (Table 6.5). In other years, mean damage varied between 17% and 24%.

Leafblister sawfly (*Phylacteophaga* spp.)

General biology

The leafblister sawflies are a group of species belonging to the endemic Australian sawfly genus *Phylacteophaga* (Hymenoptera: Pergidae). In a recent revision, Mayo, Austin and Adams (1997) recognised five species: *P. eucalypti* Froggatt, *P. froggatti* Riek, *P. occidens* Benson, *P. rubida* Riek and *P. amygdalini* Mayo, Austin and Adams. *Phylacteophaga occidens* is restricted to three localities in Perth, WA, *P. rubida* is known only from only one locality in Brisbane, Qld and *P. amygdalini* is thought to be endemic to Tasmania. Both *P. eucalypti* and *P. froggatti* occur in south-eastern Australia. *Phylacteophaga eucalypti* also occur in Tasmania, while *P. froggatti* does not and the distribution of *P. froggatti* extends further north along the eastern seaboard. *Phylacteophaga froggatti* is probably endemic to south-eastern Australia, but its distribution has recently been extended by human activity. It is now found in Tasmania, Western Australia, New Zealand and New Caledonia. *Phylacteophaga froggatti* is the most polyphagous of the leafblister sawflies and its host range includes many plantation and ornamental species. This and its ability to regularly colonise regions outside its endemic range make it the species of most concern. Farrell and New (1980) and Thumlert and Austin (1994) have described the biology of *P. froggatti* and is summarised below.

Larvae of the insect mine the leaves of eucalypts causing substantial damage to foliage. Juvenile foliage of young trees or the lower leaves of older trees are focussed. Heavy infestations can cause complete defoliation of individual trees or of entire plantations of newly planted trees. Damage by

leafblister sawfly is characterised by formation of a brown irregular blister on the leaf surface, hence its name. At low densities, each larva feeds within a separate mine, but as densities increase, mines may be joined. At high densities, the whole leaf surface can be covered with blistered tissue and ceases to be photosynthetically functional.

Eggs are oviposited under the leaf surface, often close to the midrib. A small swelling about 0.75 x 0.5 mm is formed in the leaf tissue above the egg. After 24–48 hours, the swelling turns light brown with a red surrounding annulus up to 30 mm wide. Several females may lay up to 150 eggs in a single leaf. Newly hatched larvae mine into the leaf tissue surrounding the egg. Initially the mine is linear, often following a leaf vein, but after a few days, it is opened up into the characteristic irregular rounded blotched shaped blister. Larvae pupate within the mine, forming a silk cocoon centrally in the blister. The blistered tissue is incorporated into the cocoon, resulting in a distinct wrinkled swelling in the mine. The adult cuts an oval hole through the cocoon and the overlying blister as it exits.

Phenology

The life cycle is short, lasting about six weeks in summer and several months in winter. Between four and eight generations per year are possible, depending on local conditions. Development is well synchronised and no resting stage is known.

Massive outbreaks of leafblister sawfly can occur in young plantations. With multiple generations per year, they have a high capacity for increase that enables them to escape from controls by their parasitoids. However, outbreaks can collapse as suddenly as they erupt, probably due to a combination of a build up in parasitoid numbers and decrease in availability of suitable foliage as plantations age.

Damage

The only sites to experience any substantial leafblister sawfly damage were at Deniliquin. In the autumn of 1997 an outbreak population quickly developed. Leaf damage was greatest at Barclay and in May 1997 was 11.7% and 26.3% for the *E. benthamii* and *E. dunnii* trials respectively. By September 1997, damage was 23.2% and 44.7% for each trial respectively. Damage at Crossley in 1997 was much less with 1.7% and 14.0% damage in the *E. benthamii* and *E. dunnii* trials respectively. However, by April the following year damage had reduced to less than 2% on both trials at both sites.

While tree growth at Barclay was rapid, there was a large degree of heterogeneity in tree development and it seems unlikely that reduction in the availability of suitable foliage was the explanation for the crash in the leafblister sawfly population. A more likely explanation is that by the spring of 1997, sufficient numbers of parasitoids had built up to exert control on the sawfly population over the summer of 1997–98.

Natural enemies

A number of parasitoids have been associated with *P. froggatti*. Thumlert and Austin (1994) recorded 17 species of which eleven were primary parasitoids and three were facultative parasitoids. The remaining three species had undetermined host relationships. However, species of the facultative hyperparasitoid genus *Cirrospilus* Westwood (Hymenoptera: Eulophidae) and the braconid *Bracon phylacteophages* Austin (Hymenoptera: Braconidae) are normally the most common parasitoids associated with leafblister sawfly. In Adelaide, parasitism levels ranging from 15.6% to 60.3% have been recorded, with *C. margiscutellum* (Girault) by far the most common species and *B. phylacteophages* the next most common (Thumlert and Austin 1994). In Melbourne, the later species was more abundant (Farrell and New 1980). Both *B. phylacteophages* and *C. margiscutellum* are solitary primary parasitoids of third instar to early stage pupae of *P. froggatti*. *Cirrospilus margiscutellum* is also a hyperparasite of *Bracon* spp. and other parasitoids of the sawfly.

7 Economic cost of insect damage to plantations in the Murray Valley

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Summary

We report the results of a modelling approach to investigate the economic cost of insect damage to eucalypt plantations in the Murray Valley. In particular we: 1) Developed a plant growth model which was used to simulate the productivity of a number of plantation scenarios in the Murray Valley. The plantation scenarios varied in rotation time (10 and 25 years), tree species (*Eucalyptus globulus* and *E. grandis*) and wood product (pulp and sawlogs); 2) Subjected the model tree to a range of insect attack resulting in defoliation; 3) Used productivity predictions from the plant model to carry out an economic analysis to investigate the financial impact of insect attack on projected returns for each of the plantation scenarios.

While the plant growth model appeared to adequately describe how a eucalypt allocates resources and grows, its performance was limited by the paucity of data in several critical areas of eucalypt growth and development. More data is needed in such areas as biomass partitioning and how biomass changes seasonally, ontogenetically and in responses to thinning, herbivory, and silvicultural practices such as fertilisation and irrigation. Additionally much more data is needed on carbon storage and mechanisms of compensatory growth. While field data was used to calibrate the plant growth model it has not been formally validated.

Plantation standing volume for age was variously affected by insect attack, although generally the tested plantations showed recovery of production post insect damage. However, by the end of the nominal rotation periods there were differences between species in post insect damage production recovery. Ranking mean annual increment (MAI) and internal rate of return (IRR) for different levels of insect damage showed that in all cases, given fixed financial inputs to plantation management, as MAI decreases, so does IRR. The effect of insect damage varied between the two plantation species with impact greater on the *E. globulus* plantation compared to the *E. grandis* plantation. It is likely that the longer rotation and management regime (including thinning) of the *E. grandis* plantation resulted in greater recovery of MAI and reduced IRR sensitivity.

Simulation results suggest that addition of insect management had little impact on the IRR of the *E. grandis* plantation, where as it had a larger impact on the IRR for the *E. globulus* plantation. The impact of adding insect control to monitoring had little impact on IRR for both plantation regimes. A number of management scenarios are presented to determine the range of likely outcomes for managers deciding whether or not to monitor plantations, and after monitoring, whether or not to apply insect control measures. The results are discussed in terms of risk management and the trade offs plantation managers must make between the range of available actions and the risks of adverse effects flowing from those choices.

Introduction

Modern pest management strategies require an understanding of how a given pest impacts upon its host (Abbott *et al.* 1993). Fully understanding the relationship between a pest and its host requires

consideration of a number of topics. This involves not only understanding the biology of the pest, its host and possible natural enemies, but also the economic costs both in terms of loss of yield and management strategies needed to stop or reduce such losses and environmental costs, such as insecticide resistance or non-target insecticide mortality (Bardner and Fletcher 1974; Southwood and Norton 1973; Stern 1973). Once such relationships are known it becomes possible to determine economic thresholds, above which damage is worth more than the cost of control (Speight *et al.* 1999).

Additionally, plantation managers are now under a broader range of pressures, with performance no longer assessed based on wood produced alone. They are now assessed based on the triple bottom line. Triple bottom line assessment means that a manager must consider social, environmental and economic issues as part of performance. The broader nature of assessing management could be seen as a challenge and threat by some managers, but others may consider it as an opportunity to think outside of the box and address issues in a much broader context. Such a change in management paradigm can lead to savings in operating costs and improve returns, provided that the broader stakeholder groups act responsibly in the due process of arriving at the new management regimes. Managers must now have a greater understanding of a range of issues outside of the narrow definition of plantation management, as well as understanding better the plantations that they are managing. It is no longer acceptable to manage by prescription. Now a plantation manager must determine what management inputs are required on a compartment by compartment basis.

Tree growth rates are one of the key determinates of agroforestry financial return and benefit (Wong *et al.* 2000). It is important for both landholders and investors to be able to predict growth of a given tree species on particular sites. It is also vital for those managing plantations to be able to predict changes to growth rates as a result of events such as pest attack during the life of a plantation. With this knowledge managers can make choices informed by social and environmental issues, as well as economic ones, about the costs of control options when faced with pest outbreaks.

While outbreak species like stick insects (Phasmatidae) (Mazanec 1966) can potentially damage trees of any age, severe defoliation in the first three to four years of a plantation, generally the period prior to canopy closure, is thought to be the most serious threat to plantation profitability (Collett and Neumann 2002). Data on the impact of insect damage on growth has been collected for many commercially important eucalypt species: *E. delegatensis* R.Baker (Mazanec 1966), *E. grandis* (Carne *et al.* 1974a; Wilkins 1990), *E. marginate* Donn ex Sm. (Abbott *et al.* 1993), *E. nitens* (Deane & Maiden) Maiden (Candy 1999), *E. regnans* F.Muell. (Candy *et al.* 1992a; Cremer 1972; Cremer 1973; Elliott *et al.* 1993) and *E. globulus* Labill. (Collett and Neumann 2002). Additionally data on the impact of insect damage on the growth of *E. grandis* (Chapter 2), *E. globulus* (Chapters 4–5), *E. benthamii*, *E. dorrigoensis*, *E. dunnii*, *E. kartzoffiana* and *Corymbia* spp. (Chapter 3) are presented in this report.

The impact of defoliation on young eucalypts is dependent on the interaction of the following factors: 1) severity or intensity and frequency of defoliation episodes within and between years; 2) the season of the year when defoliation occurs; 3) the location within the crown of the damage and 4) the age, vigour and species of attacked tree (Abbott *et al.* 1993; Carne *et al.* 1974a; Collett and Neumann 2002; Cremer 1972; Cremer 1973; Ohmart *et al.* 1983). While some species (e.g. *E. delegatensis* (Mazanec 1966)) are more susceptible to damage than others, commercially important eucalypt species can generally sustain relatively high one-off defoliation events when grown under optimal condition. For example, Carne *et al.* (1974) reported that vigorously growing young *E. grandis* can tolerate up to about 50% defoliation with no measurable impact on growth increment.

Levels of stored carbohydrates are thought to be important in determining how a tree responds to defoliation. For eucalypts it has been suggested that starch reserves are important in determining how well trees recover from defoliation. Bamber and Humphreys (1965) showed that starch reserves fluctuated annually being lowest at the end of the growing season, increased during winter and reached a peak just prior to the new growing season in spring. Starch levels also declined as trees were defoliated, the extent of the decline being greater than the normal seasonal decline in undamaged trees.

Based on these observations they suggested a mechanism to explain how insect damage impacts on forest trees. Repeated defoliation results in depleted starch reserves. If the reserves are sufficiently depleted, production of new leaves is reduced or prevented. The combination of little or no foliage and reduced starch reserves results in insufficient metabolism to support respiration or growth, leading to tree mortality. With less severe defoliation tree mortality is not as likely, but depending on the season of attack and the levels of starch reserve, growth loss may occur because starch reserves are too low to compensate for the damage. This mechanism is thought to explain why defoliation in late summer and autumn more seriously affects trees than similar defoliation episodes at other times of the year. Starch has also been implemented in the responses to herbivory in other forestry species (Ericsson *et al.* 1980; Kulman 1965; Rook and Whyte 1976; Webb and Karchesy 1977).

In studies measuring the impact of insect damage, observations are usually made in the immediate period (usually one to two years) after the damage event. There is little published data on the impact of insect damage over the commercial life of a plantation. Plantation rotation times are variable, depending on the species and major wood product, but usually range from 8–10 years for pulp to 20–25 years for sawlogs. Measuring damage impacts over the life of the plantation, not just immediately after the damage event, is important. While some financial returns can be made from a plantation during its life (for example, pulping the wood from non-commercial thinning), full financial returns are only realised when the whole plantation is harvested. Only then can the economic impact of insect damage either through reduced yield or loss of wood quality, be calculated.

Projections of wood loss over the life of a plantation based on growth increment suppression for one to two years after a damage event are unlikely to be accurate. This is because of compensatory growth. Plant compensatory growth following insect damage is a general occurrence of considerable importance in both natural and agricultural systems (Trumble *et al.* 1993). Defensive adaptations, such as compensatory growth that allow a plant to sustain tissue loss with little or no loss of yield (Trumble *et al.* 1993) or fitness (Stowe *et al.* 2000), are examples of plant tolerance. This is distinct from plant resistance which includes defensive adaptations that prevent or reduce tissue damage.

The importance of compensatory growth has long been recognised in agriculture (Bardner and Fletcher 1974; Southwood and Norton 1973; Stern 1973; Trumble *et al.* 1993) and the implications for plantation management are potentially substantial. If over the commercial life of a plantation, trees can sustain periods of moderate to heavy damage and suffer no loss of yield, then the economic bases on which management decisions are made change considerably.

Rapid growth is a common trait of commercially important eucalypt species and Stone (2001) has argued that plantation eucalypts defend against herbivory through inherently high growth rates. Plant herbivore defence theories predict that intrinsically fast growing species are less likely to invest in resistant traits (such as defensive chemicals) than slower growing species but are more likely to exhibit tolerant traits (such as compensatory growth) because of higher foliar growth rates (Coley *et al.* 1985). Studies comparing herbivory on fast and slow growing plant species in temperate and tropical communities support this prediction. In 20 out of 21 communities studied, fast growing species had higher herbivory than slow growing species (Coley and Aide 1991). Faster growing plants with high inherent levels of herbivory are more likely in resource-rich habitat than in resource-limited habitats, while resource-limited habitats are more likely to support slower growing, chemically defended plants (Stone 2001). It has been predicted that under optimal conditions a doubling of growth rate has the equivalent effect on plant development as a 50% reduction in herbivore pressure (de Jong 1995).

One of the difficulties in determining how important tolerance is to plantation eucalypts is the resources needed to complete the required experiments. Needing to run over 10–25 years with continual monitoring and measurement of growth and insect damage, the cost in terms of person-power, operating funding and site availability are likely to constrain attempts to run such experiments. The compromises needed to work around such constraints inevitably lead to inadequate experimental

design, with a resultant loss of statistical power and ability to deliver convincing outcomes (Raffaelli and Moller 2000). The cost benefits of such experiments then become questionable.

One approach to such resource problems is to model the system under study and simulate experiments. This has several additional benefits besides reducing costs. The model building process can crystallise important properties of a system. It can also make it easier to think about the problem or process under consideration by concentrating effort on identifying and characterising the essential components needed to make the model work. Models can shed light on the real world they mimic by showing properties that previously were not apparent. Additionally model building can highlight the limits of current knowledge, particularly basic assumptions about how a system works. If a model does not behave as expected then the underlying assumptions of the modelled system may be wrong. Importantly models can also make predictions that can be tested experimentally.

In this chapter we report the results of a modelling approach to investigate the economic cost of insect damage to eucalypt plantations in the Murray Valley. In particular we:

1. Developed a plant growth model which was used to simulate the productivity of a number of plantation scenarios in the Murray Valley. The plantation scenarios varied in rotation time, tree species and wood product.
2. Subjected the model tree to a range of insect attack resulting in defoliation.
3. Used productivity predictions from the plant model to carry out an economic analysis to investigate the financial impact of insect attack on projected returns for each of the plantation scenarios.

Based on our results we set out management recommendations for control of pest outbreaks on eucalypt plantations in the Murray Valley.

Materials and methods

An overview of damage modelling

The aim of model development was to be able to test the impact of likely insect damage scenarios and management actions on the amount of wood produced and the financial returns of that wood flow. A model was prepared in two parts: development of a wood flows physical budget and then application of costs and returns information over the wood flows to give financial returns. Preparation of the physical budget components was based on Jenkins (1992) and in part Australian Greenhouse Office (1998). Figures 7.1 and 7.2 outline the steps in model development. The model is based on an Excel™ spreadsheet, with all components within the spreadsheet. A separate spreadsheet was developed for each plantation regime tested.

Physical budgets

Plantation regimes

Plantation regimes were developed to suit the conditions of the Murray Valley based on information provided by the Murray Riverina Farm Forestry Regional Plantation Committee (Scott 2002), industry standards and experience, and the South African solid wood management regimes (Jenkin 1992). It was assumed that the plantations were established and managed based on best practice principles to reduce tree stress. In reality, it may be that periods of tree stress (e.g. due to drought) may result in insect attack, but for the sake of this analysis, all likely plantation management inputs and costs have

been assumed as included. A broad number of assumptions were made, including that given enough resource, processing facilities would be developed in Shepparton, and that plantation produced woodchips could be exported from the Port of Geelong (with transport by rail from Shepparton).

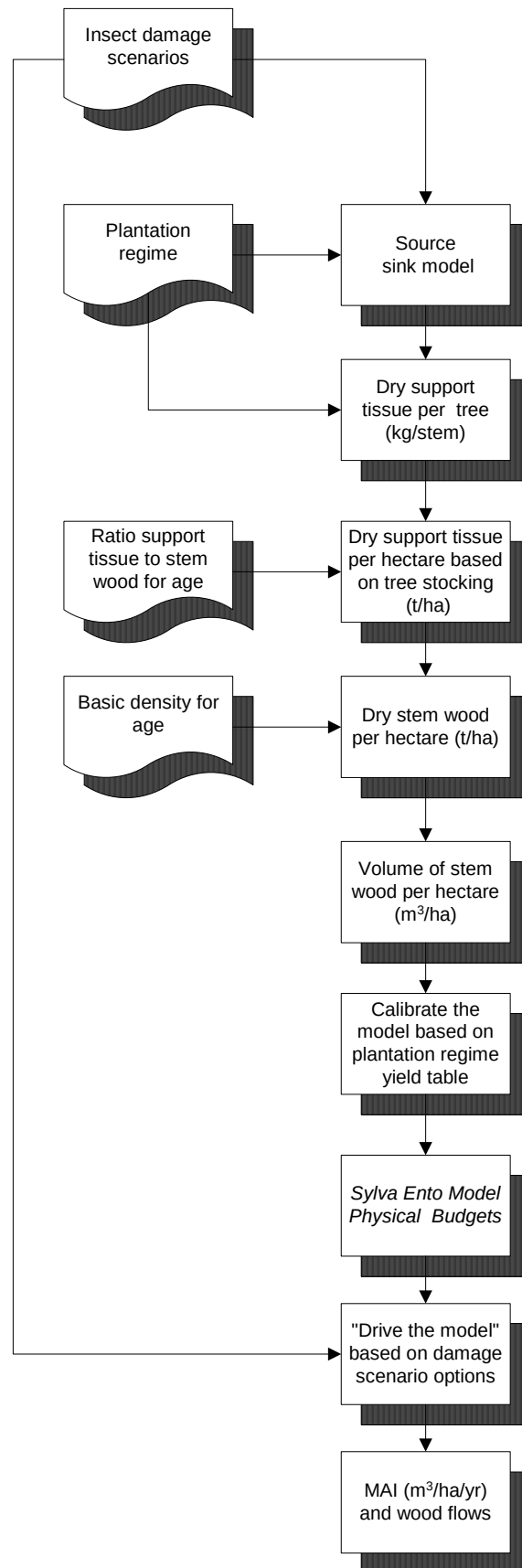


Figure 7.1 An outline of the Sylva Ento Model, showing the stages of the model for the physical budget

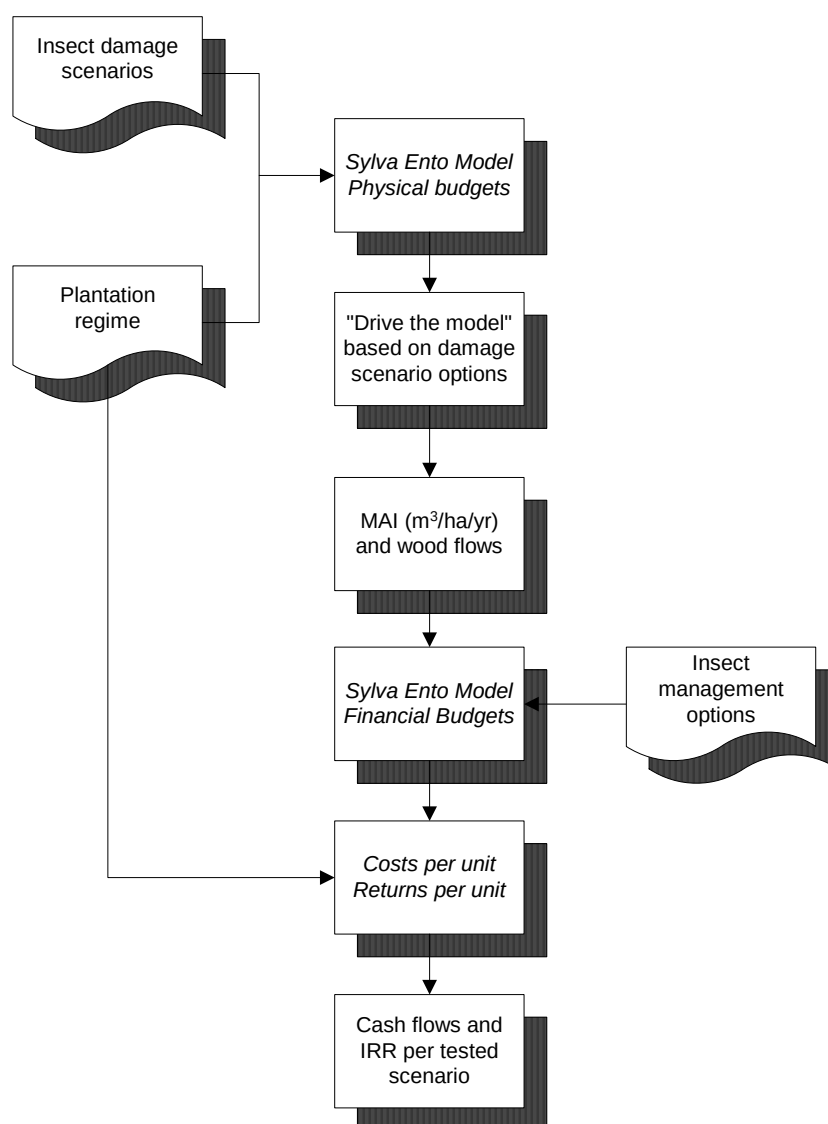


Figure 7.2 An outline of the Sylva Ento Model, showing the stages of the model for the financial budget

Table 7.1 gives an overview of each of the plantation regimes (details of wood flows, expenses and revenues are presented in Appendix 1).

Plantation yield table for the species of interest, under irrigation and in dry lands were prepared based on Wong *et al.* (2000). The yield tables for *E. globulus* growing in Victoria were used to generate yield curves resulting in the target mean annual increment (MAI) by “shifting” the yield curves up or down based on a set percentage.

Establishment and management costs were prepared based on Murray Riverina Farm Forestry Regional Plantation Committee (Scott 2002), industry standards and experience. Target products were allocated based on likely possible markets, plantation attributes and information from the Murray Riverina Farm Forestry group. Product price assumptions were based on discussions with the Murray Riverina Farm Forestry group and Ausnewz (2001). Irrigation expenses were based on information from the Murray Riverina Farm Forestry Regional Plantation Committee (Scott 2002).

Damage scenarios

Damage scenarios were designed to reflect known relationships between insect damage and tree growth. They were derived either from data presented elsewhere in this report (see Chapters 2–5), from the literature on insect impacts on eucalypt growth or from unpublished observations. Scenarios were chosen to investigate the relationship between damage severity and 1) timing of damage both within and between seasons 2) frequency of damage and 3) tree age. Finally some scenarios were designed to allow analysis of the behaviour of the plant growth model. In all scenarios a total of fifty different scenarios were used, but not on all species (Appendix 2).

Table 7.1 An overview of the plantation regimes analysed. (See Appendix 1 for wood flows, expenses and revenues)

Plantation attribute	Species	
	<i>E. globulus</i>	<i>E. grandis</i>
Target product	Pulpwood	Solid wood
Rotation (yrs)	10	20
Mean annual increment (m ³ /ha/yr)	30	25
Initial stocking (stems/ha)	1100	1100
Thinning	Nil	Yes
Irrigation	Yes	Yes

Source–sink plant growth model

There are various models of eucalypt growth which have been used to predict site productivity such as ProMod, CABALA, and 3PG (Battaglia and Sands 1997; Landsberg and Waring 1997; Sands *et al.* 2000), but none of these are suited for examining the effects of defoliation on productivity because they do not consider stored carbohydrates. Stored carbohydrates are thought to be important in producing new leaves after severe defoliation (Cannell and Dewar 1994; Jarvis and Leverenz 1983; Trumble *et al.* 1993).

We modified an existing but unpublished source-sink model of plant growth based on carbohydrate translocation between different plant parts (Matsuki 1997). In our model, a tree was divided into various components or plant parts—foliage, roots, storage, and support tissue (bark, branches and stem wood). Trees changed carbohydrate allocation patterns between these components within a given year, during its ontogeny, and in response to external factors such as management (i.e. thinning), insect defoliation, drought, and irrigation (Cannell and Dewar 1994). Allocation patterns of carbohydrates into different plant parts were determined from published information or based on our personal observation. The model output for each species was based on the plantation management regimes, in particular, the change in stocking rates due to thinning. For each of the species of interest the model was calibrated using published information of biomass allocation (Australian Greenhouse Office 1998; Beadle and Inions 1990; Bradstock 1981; Cromer and Jarvis 1990; Cromer and Williams 1982; International Greenhouse Partnerships Office 2001; Linder 1985; Wong *et al.* 2000).

After the carbohydrate allocation patterns were determined, we adjusted model growth parameters so that the model tree without defoliation showed growth patterns matching that of real trees in plantations without defoliation (see growth trial results in Chapters 2–4). The data on growth of defoliated trees obtained in the trials described in previous chapters of this report were also used to calibrate parameters for compensation mechanisms. This also helped to partially compensate for limitations in the available data for some species. We then imposed various defoliation scenarios to this base model.

There are two unique features of our model that make it suitable for studying effects of defoliation on growth. Firstly, it considers allocation of stored carbohydrates for growth in spring, and after

defoliation. Secondly, our model incorporates three mechanisms of compensation after defoliation: (1) increased photosynthesis; (2) increased allocation of carbohydrates to foliage after defoliation; and (3) increased mobilisation of stored carbohydrates after defoliation. Many plants are known to compensate for lost foliage (Stowe *et al.* 2000; Strauss and Agrawal 1999; Tiffin 2000; Trumble *et al.* 1993).

The output of the source-sink model is the dry weight of individual tree support tissue (kg/stem). Support tissue is defined as the above ground biomass less the leaves. A table of individual tree dry weights per stem per age was generated and used as the link into the *Sylva Ento Model*.

Sylva Ento Model

The *Sylva Ento Model* was prepared to take the source-sink model outputs and generated the required physical budgets to allow analysis of the physical (i.e. change in MAI) and financial (i.e. change in internal rate of return (IRR)) performance of each of the damage scenarios. The model allows analysis of a wide range of plantation management options, insect management (e.g. monitoring and control) and expenses and returns.

Support tissue per hectare was estimated based on the sink-source model outputs multiplied by the plantation stocking rates each year.

$$ST_{t\ dry\ i} = (S_{kg\ dry\ i} \times SPH_i) / 1000$$

Where:

$ST_{t\ dry\ i}$ = Standing weight of dry support tissue (t/ha) at year i

$S_{kg\ dry\ i}$ = Standing weight of dry support tissue (kg/tree) at year i

SPH_i = Stocking rate (stems/ha) at year i

The model output of dry weight of support tissue per hectare was converted to dry weight of stem wood per hectare based on the ratio of stem wood to support tissue. The ratio was estimated based on an analysis of a series of published eucalypt biomass data (Bradstock 1981; Christie and Button 1991; Frederick *et al.* 1985a; Frederick *et al.* 1985b). Other authors have used biomass allocation relationships for conifers (i.e. International Greenhouse Partnerships Office (2001)). Stands of eucalypts have different dynamics (i.e. crown closure and crown retreat), which will alter the allocation of biomass material with age, hence the preference to use eucalypt specific functions. The following lists the function used.

$$R_{sw\ to\ st\ i} = (0.15 \times \ln(age_i)) + 0.4$$

Where:

$R_{sw\ to\ st\ i}$ = ratio of stem wood to support tissue on a dry weight basis at age i

$\ln(age_i)$ = the natural log of age i

Support tissue per hectare was converted to stem wood per hectare as follows for each age.

$$SW_{t\ dry\ i} = ST_{t\ dry\ i} \times R_{sw\ to\ st\ i}$$

Where:

$SW_{t\ dry\ i}$ = weight of dry stem wood per hectare (t/ha) at age i

Plantation productivity is usually expressed in volume grown per hectare per year (mean annual increment $m^3/ha/yr$). Dry stem wood per hectare is converted to volume based on the basic density of the tree wood. Basic density is the bone-dry mass of solid wood per green wood volume (Bootle 1985). Bone-dry is determined by weighing the wood when green, putting it into an oven and drying it until the weight remains constant (that is, there is no more water to be dried from the wood). Basic density varies within trees (Washusen 1998), between trees (Tibbits *et al.* 1990), with age (Whiteman 1997) and growth rates (Downes *et al.* 1997). Basic density is a key driver of calculated returns as it affects the bone-dry weight of wood sold (i.e. woodchips are sold on a bone-dry metric tonne basis) and the handling costs (i.e. freight costs). Each eucalypt plantation will have a mean basic density. A basic density with age function was developed based on a number of published reports for *E. globulus globulus* Labill (Borrallho *et al.* 1993; Dean *et al.* 1990; Downes *et al.* 1997; Hicks and Clark 2001; Ilic *et al.* 2000; Kibblewhite *et al.* 2001; Northway and Blakemore 2001; Phillips 1988; Raymond and Muneri 2001; Tibbits *et al.* 1990; Whiteman 1997; Williams 1994; Yang and Waugh 1996). The *E. grandis* plantation regime was assumed to have similar basic density attributes with age.

The following lists the function used.

$$BD_i = (60 \times \ln(age_i)) + 390$$

Where:

BD_i = basic density at age i expressed as kg/m^3

$\ln(age_i)$ = the natural log of age i

Dry weight of stem wood was converted to volume based on

$$V_i = BD_i \times SW_{t\ dry\ i}$$

Where:

V_i = volume at age i (m^3/ha)

The output of the *Sylva Ento Model* was calibrated against the standard yield table for the species tested. This was done by comparing the nil damage scenario with the developed yield tables, and shifting the output of the *Sylva Ento Model* to match the standard yield table. The assumption was made that the standard yield table was based on a nil damage situation. All other damage scenario outputs were adjusted by the same amount.

Any aspect of the plantation physical budget can be recorded for analysis and/or comparison. The main one used is the resultant MAI for each plantation regime as impacted by the applied damage scenario.

Financial budgets and models

Each of the generated physical product flows will have associated expenses and revenue. Between tested regimes, both the quantum and timing of expenses and revenue will vary to give a “unique” cash flow profile. Any economic evaluation must take account of such differences. IRR analysis of the full cash flow is the preferred method of plantation regime and damage scenario economic evaluation as it eliminates the need to choose a discount rate. The *Sylva Ento Model* generates a cash flow profile

for the developed plantation regime and damage scenario based on the inputted cost data as applied to the generated physical budget. The IRR of that cash flow is calculated and reported.

Analysis undertaken

Standing volume by age

A complete data set for standing volume by age for each of the insect damage scenarios and the *E. grandis* and *E. globulus* plantation regimes was compiled. It did not include any management intervention options.

Impact on MAI and IRR

Analysis was completed to generate a data set to show the impact of each insect defoliation scenario on the *E. grandis* and *E. globulus* plantation regimes. The analysis did not include any management interventions for insect control.

Effect of insect damage scenarios: for each tree species

The individual data sets for the *E. grandis* and *E. globulus* plantation regimes were analysed to show the percentage change in IRR when compared to the base nil damage scenario and nil management inputs scenario. The impact of the addition of monitoring and on fixed wing application of synthetic pyrethroids was added to the analysis to show the effect on IRR of such management choices.

Effect of insect damage scenarios: comparing tree species

The individual data sets for the *E. grandis* and *E. globulus* plantation regimes were analysed to show the percentage change in IRR when compared to the base nil damage scenario. The resulting data were then placed on the same chart to show the relative sensitivity of the two plantation regimes to the insect damage scenarios. Separate charts were produced for MAI, IRR (nil insect management inputs), IRR (including monitoring) and IRR (including monitoring and insect control).

Plantation management decisions

A plantation manager must make trade offs between a range of courses of action and the risk of any adverse effect. A number of management scenarios were assembled based on the *Sylva Ento Model* outputs for the damage scenarios tested. The aim was to determine the range of likely outcomes of managers deciding whether or not to monitor the plantation, and after monitoring, whether or not to apply insect control measures. The scenarios tested are given in Table 7.2. In the text, damage scenarios are identified as S *n* where *n* = the damage scenario number in Table A2.1. It is assumed that the initial plantation grow is optimal as a result of good management (S 0 is an option).

Other management choices to be tested include:

- the impact of insecticide application methods
- the trade off between monitoring and insecticide application.

Comparisons are made between the *E. grandis* and *E. globulus* plantation regimes as affected by the different damage and intervention strategies.

Table 7.2 Management scenarios used to examine control strategy trade offs for the modelled plantations. See text for an explanation of damage scenario codes.

No.	Description
1	• 30% defoliation in late summer of year 1(S 4) • followed by up to 80% defoliation early summer in the same year (S 12) • with light defoliation continued each year up to year 4 (S 29) • OR that defoliation does not commence till year 3, when the trees receive a light defoliation in early summer, followed by a heavy defoliation in late summer (S 32)
2	• up to 30% defoliation occurs in early summer of year 1 (S 3) • followed by up to 80% defoliation in late summer (S 31)
3	• up to 30% defoliation occurs in early summer of year 3 (S 7) • with insect attack continuing in late summer with up to 80% defoliation (S 32)
4	• up to 30% defoliation in winter of year 1 (S 1) • with up to 100% defoliation occurring in winter of year 2 (S 26)
5	• an outbreak (100% defoliation) occurs in winters of year 2 and 3 (S 42) • OR an outbreak (100% defoliation) occurs in the winter of year 2 and 5 (S 46) • OR an outbreak (100% defoliation) occurs in the winter of year 2 and 9 (S 47)

Results

Standing volume by age

Plantation standing volume for age was variously affected by the damage scenarios and the ability of tree species (with given management) to recover from that damage (Figures 7.3 and 7.4). Regardless of the scenario tested, generally standing volume converged back to the norm by the end of the nominal rotation period. Plantations that initially lost standing volume were generally able to commence recovery of lost production and standing volume while plantations that initially gained standing volume commence to loose the extra production.

There was a difference in the recovery of production post insect damage by the end of the nominal rotation between the species tested (compare Figures 7.3 and 7.4). It is uncertain whether this is due to species, management options or time (or a combination). In summary, the plantations tested show a recovery of production post insect damage.

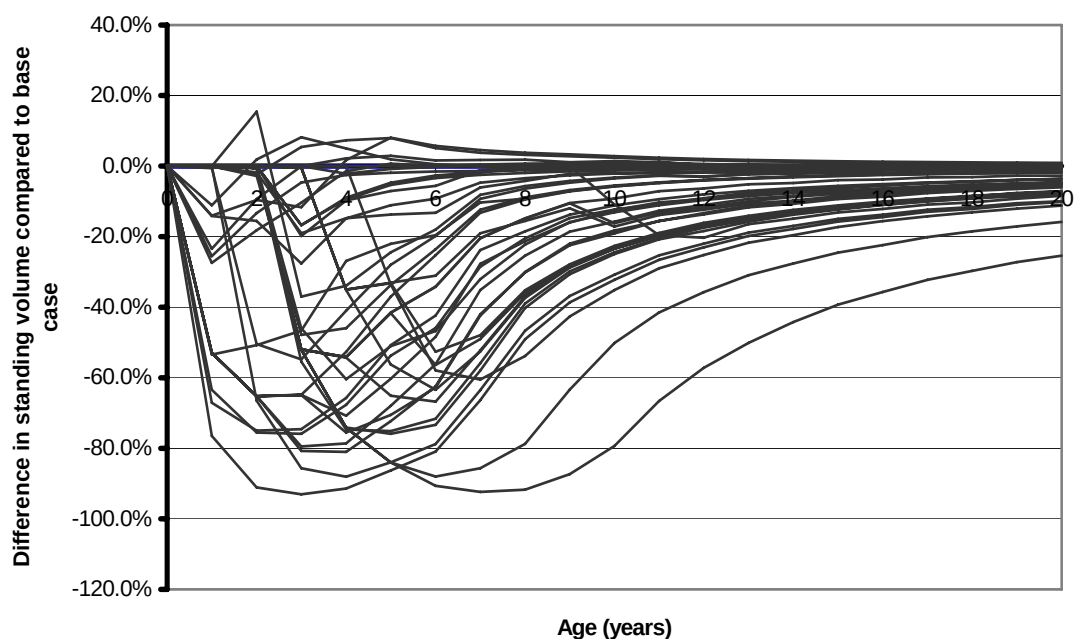


Figure 7.3 The effect of the damage scenarios on standing volume for the *E. grandis* plantation regime. The base case of nil damage runs at 0% difference, and when modelled damage reduces the standing volume, the percentage shown expresses the difference to the base case. The individual damage scenarios are not labelled, as the aim is to show the general trend of recovery with time after a damage event. Given time (longer plantation rotation), *E. grandis* plantations may recover well from most insect attack.

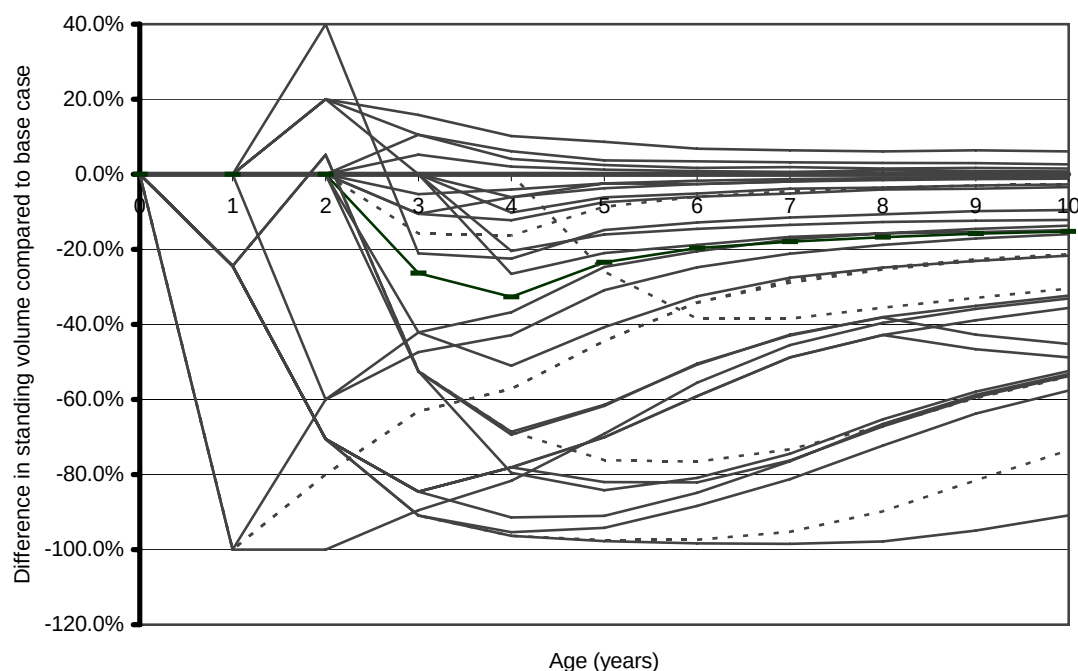


Figure 7.4 The effect of the damage scenarios on standing volume for the *E. globulus* plantation regime. The base case of nil damage runs at 0% difference, and when modelled damage reduces the standing volume, the percentage shown expresses the difference to the base case. The individual damage scenarios are not labelled, as the aim is to show the general trend of recovery with time after a damage event. Due to the shorter rotation, the *E. globulus* plantation does not have time to recover to the same extent as the *E. grandis* plantation.

Impact on MAI and IRR

The resulting MAI and IRR for each insect damage scenario was ranked and plotted for each plantation regime (Figures 7.5 and 7.6). In all cases, given fixed financial inputs to plantation management, as MAI decreases, so does IRR. The effect of the damage scenarios is different between the two plantation regimes, in that the rank based on impact on MAI, changes. As well, the impact of the damage scenarios would appear to be greater on the *E. globulus* plantation compared to the *E. grandis* plantation. It is interesting to note that damage scenarios 1, 3, 4, and 5 for both species and 30 for *E. globulus* and 29 for *E. grandis* resulted in an increase in MAI (see Appendix 2 for details). This may be an aberration of the models, or a possible outcome. In all these damage scenarios, defoliation is less than 30%. For scenarios 1, 3, 4, and 5 defoliation is once off while scenarios 29 and 30 simulate chronic low levels of defoliation (10–20%) over summer.

Effect of insect damage scenarios: for each tree species

To bring the financial impact of each damage scenario to a common base, the percentage change in IRR was calculated based on the nil damage scenario. This allows some indication of the sensitivity of the two plantation regimes to the damage scenarios. The impact of including plantation monitoring and one aerial application of synthetic pyrethroids was included in the analysis. Overall, the *E. grandis* regime was less sensitive to the insect damage scenarios compared to the *E. globulus* scenario, as measured by change in IRR (Figures 7.7 and 7.8). It is suspected that the longer rotation and management regime (including thinning) of the *E. grandis* plantation resulted in greater recovery of MAI and reduced IRR sensitivity.

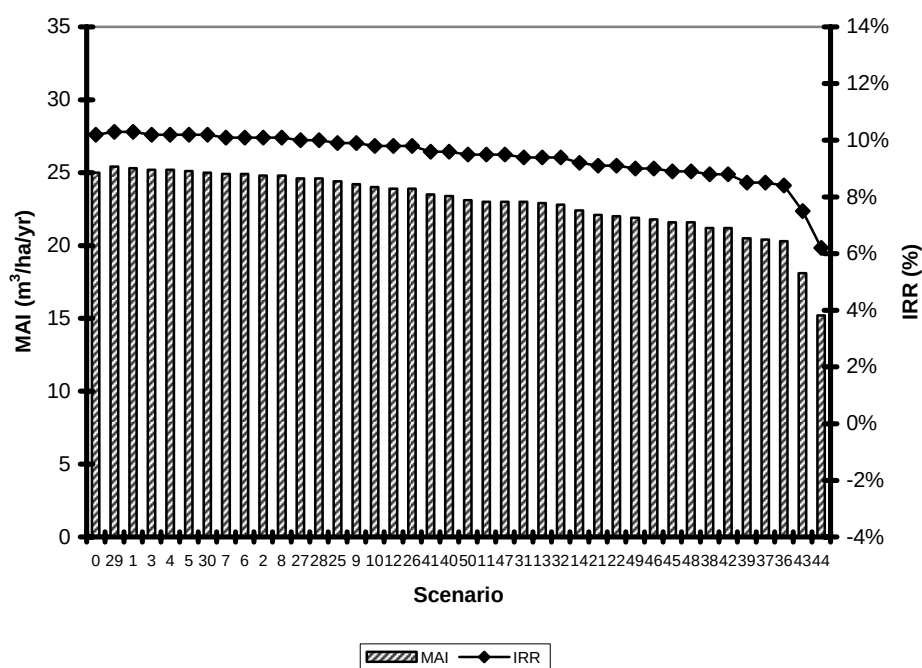


Figure 7.5 The effect of the damage scenarios on MAI and IRR for the *E. grandis* plantation regime. See Table A2.1 for damage scenario details.

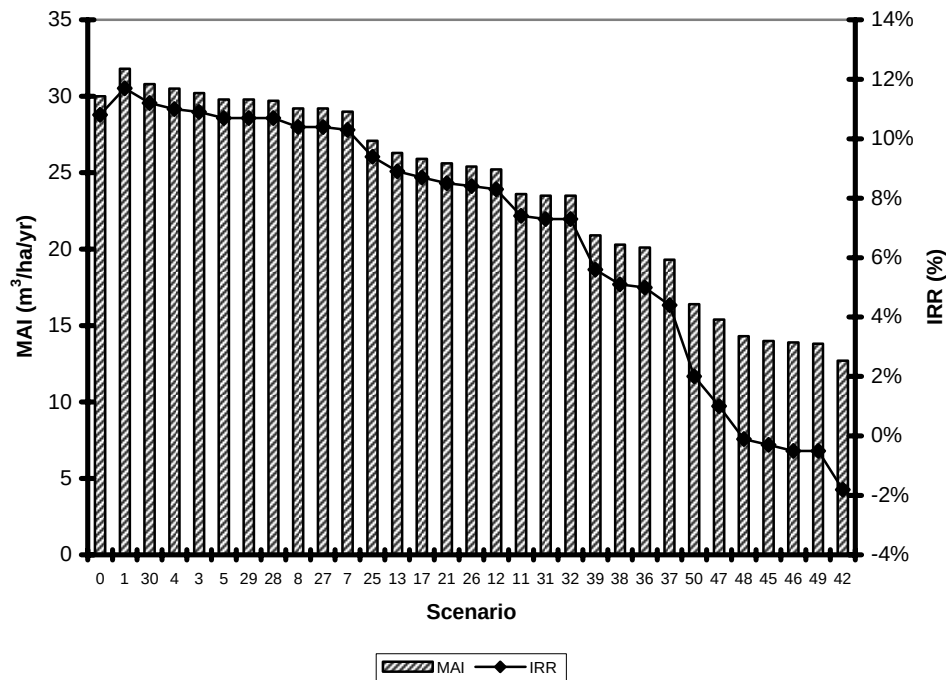


Figure 7.6 The effect of the damage scenarios on MAI and IRR for the *E. globulus* plantation regime. See Table A2.1 for damage scenario details.

Effect of insect damage scenarios; comparing tree species

The addition of insect management had little impact on the IRR of the *E. grandis* plantation (Figure 7.7), where as it had a larger impact on the IRR for the *E. globulus* plantation (Figure 7.8). The impact of adding insect control to monitoring had little impact on IRR for both plantation regimes (Figures 7.7 and 7.8).

In order to better understand the relative impact of the damage scenarios on the two plantation regimes, the change in MAI (compared to the nil damage scenario) was plotted for each species on the same axis (Figure 7.9). A similar approach was taken for the impact on IRR for the two species with nil management, addition of monitoring and the addition of follow up insect control (Figures 7.10–7.12). For all the damage scenarios where both *E. grandis* and *E. globulus* were tested, *E. globulus* was more sensitive to insect damage as indexed by the change in MAI and IRR.

Plantation management decisions

The following flow diagrams summarise how the tested plantation management decisions interact with various damage scenarios. Management decisions are included as options, with the “outcome” expressed as MAI and IRR. The insect damage scenarios impact on MAI and the management costs affect IRR. In the cases shown, the management options are monitoring and intervention. Monitoring is assumed to be plantation inspections, and adds a labour cost to the plantation cash flows. If a decision to intervene is made, the costs of insecticide application (materials and application costs) are added to the plantation cash flows. It is possible to reduce IRR by increasing costs, and MAI remains constant, (i.e. where insect damage was prevented by insecticide application as a result of monitoring). The management scenarios descriptions in Table 7.2 are repeated here to aid interpretation.

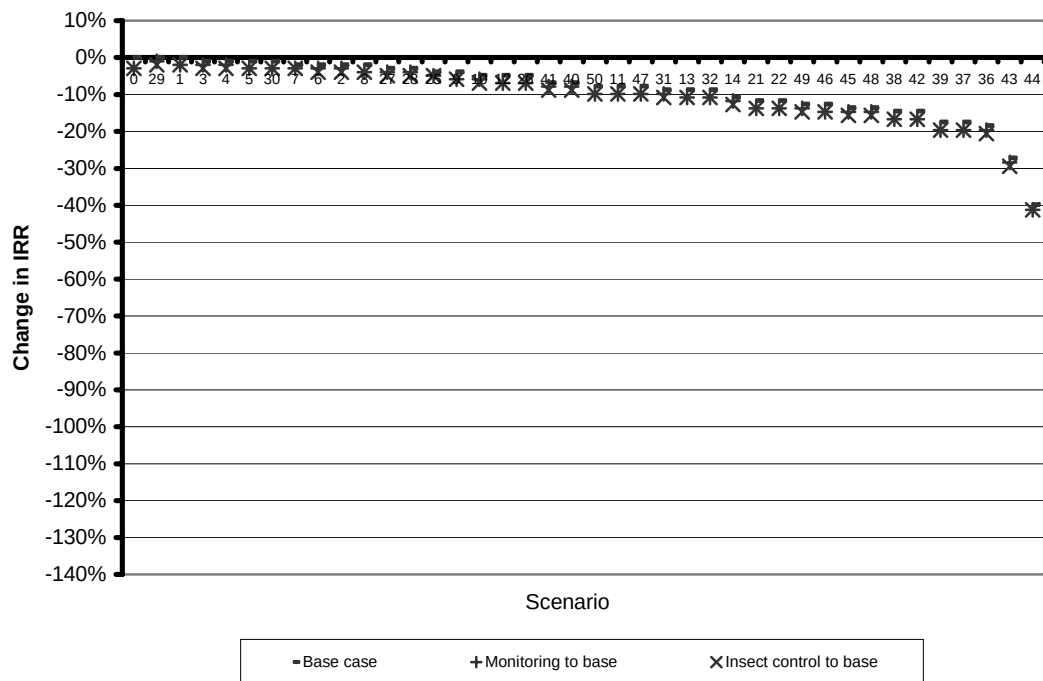


Figure 7.7 The effect of the damage scenarios on IRR for the *E. grandis* plantation regime, with the impact of the addition of monitoring and one application of insecticide. See Table A2.1 for damage scenario details.

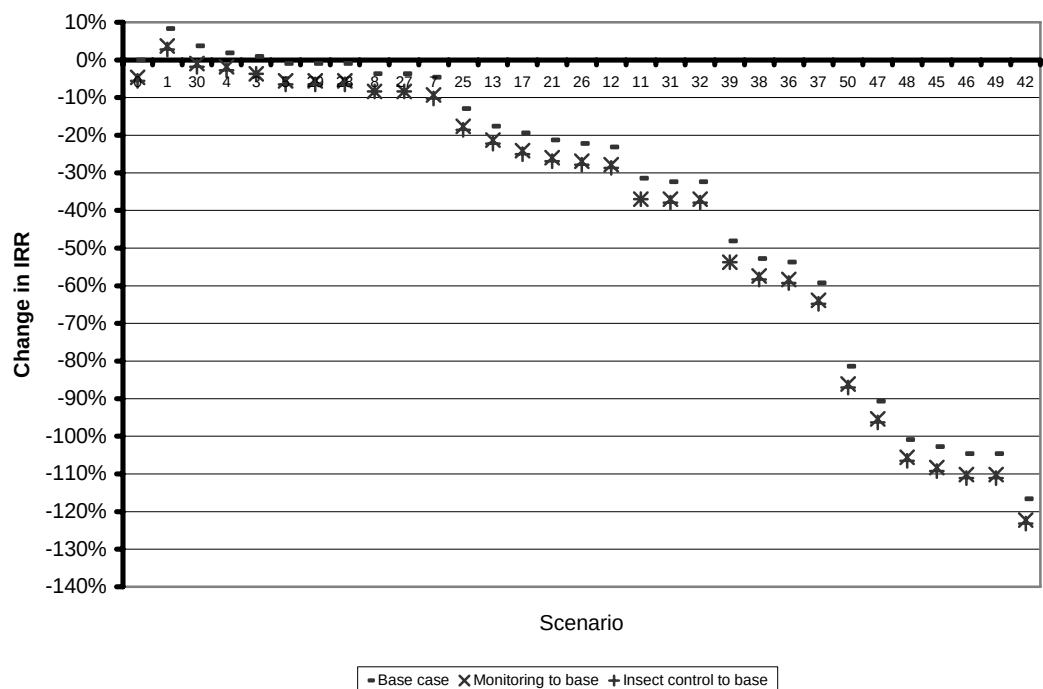


Figure 7.8 The effect of the damage scenarios on IRR for the *E. globulus* plantation regime, with the impact of the addition of monitoring and one application of insecticide. See Table A2.1 for damage scenario details.

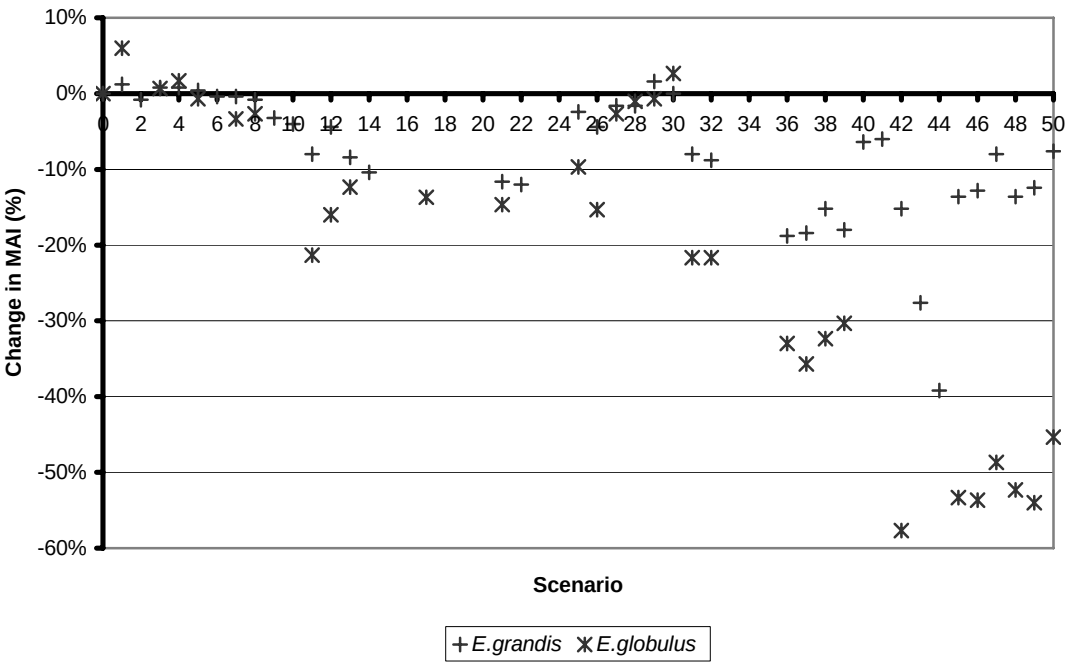


Figure 7.9 The effect of the damage scenarios on MAI for the plantation regimes tested, when compared to the nil damage base case scenario. See Table A2.1 for damage scenario details.

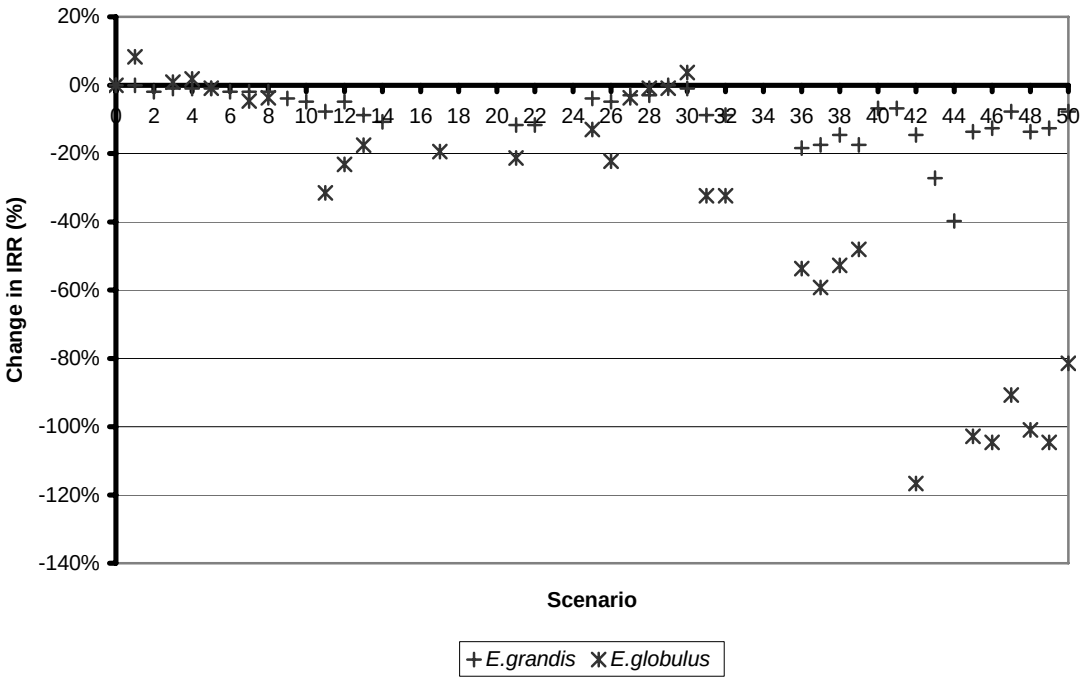


Figure 7.10 The effect of the damage scenarios on IRR for the plantation regimes tested, when compared to the nil damage base case scenario. There are nil insect management inputs. See Table A2.1 for damage scenario details.

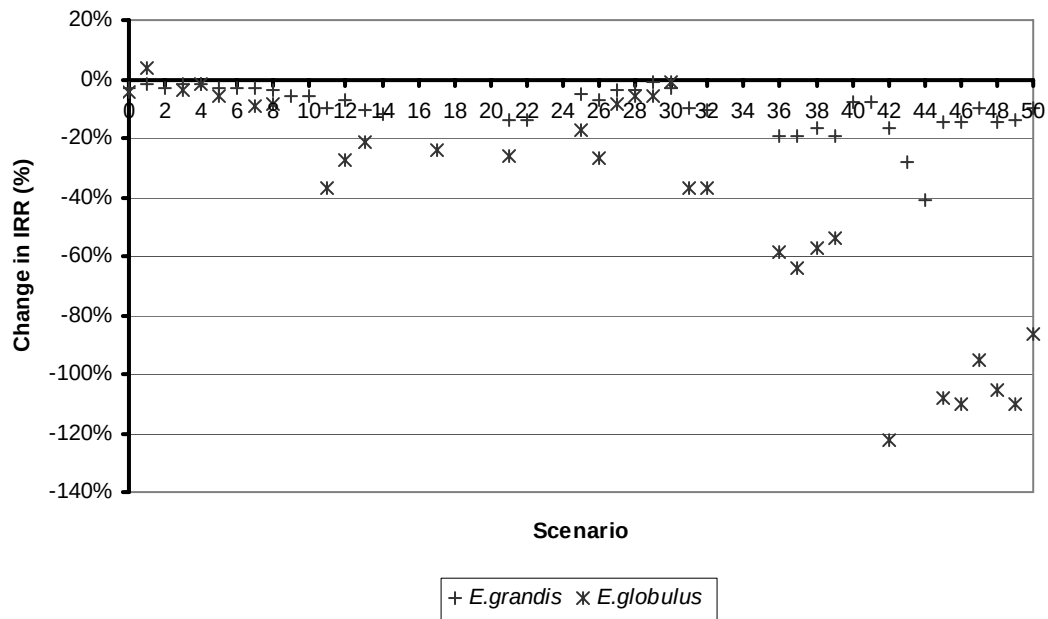


Figure 7.11 The effect of the damage scenarios on IRR for the plantation regimes tested, when compared to the nil damage base case scenario. The plantations are monitored for insect attack as part of a management regime. See Table A2.1 for damage scenario details.

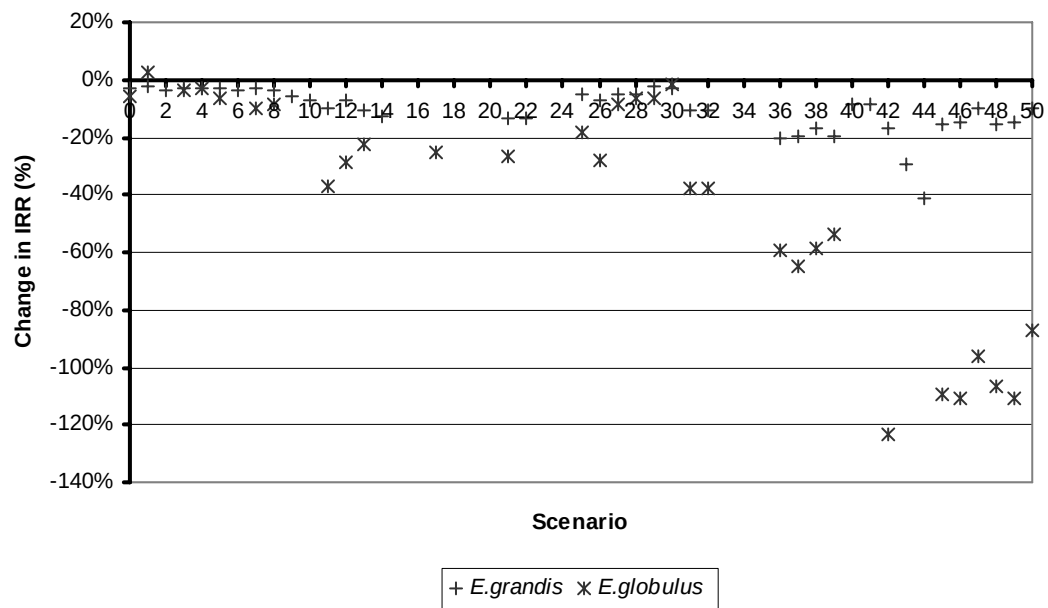
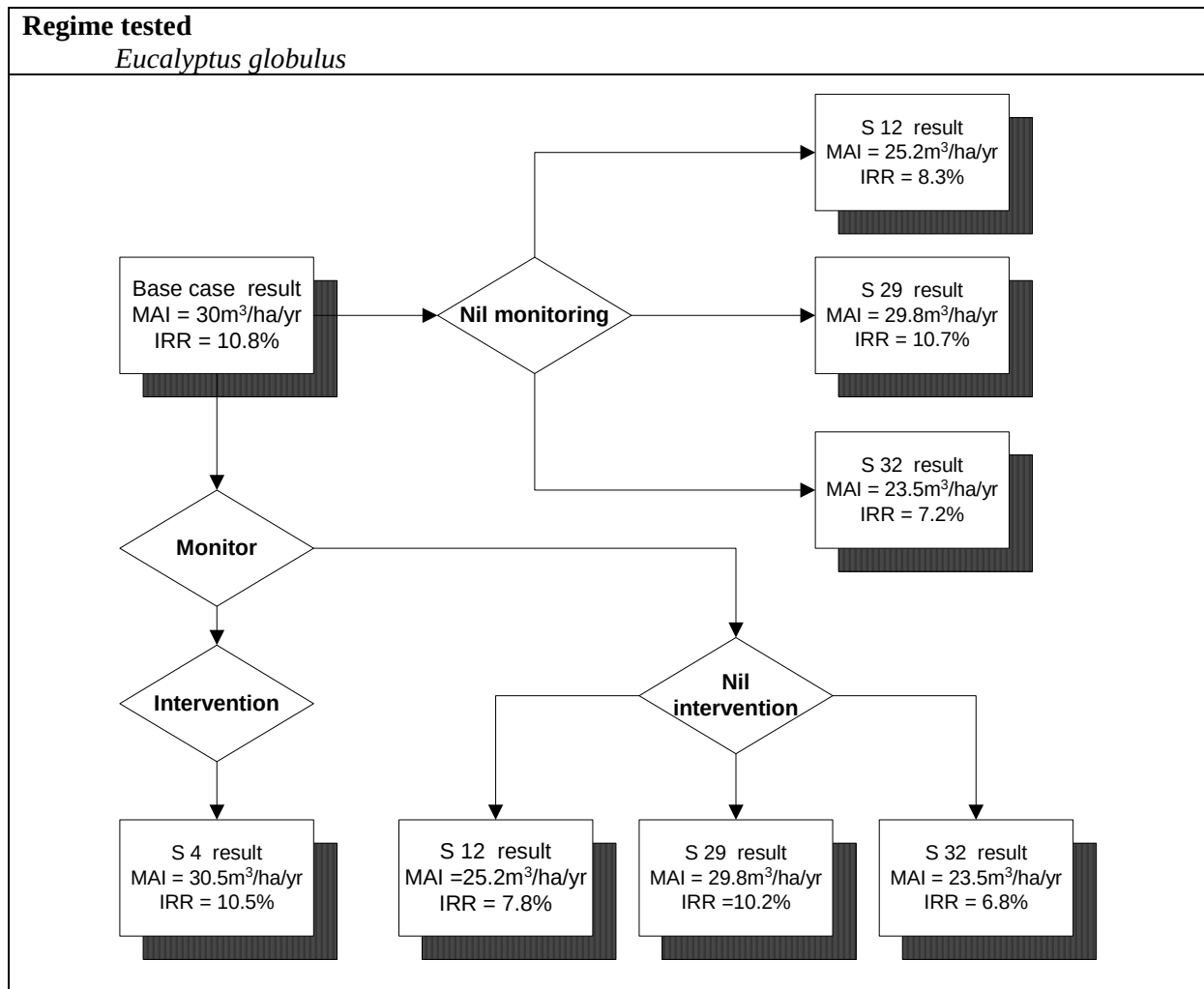


Figure 7.12 The effect of the damage scenarios on IRR for the plantation regimes tested, when compared to the nil damage base case scenario. The plantations are monitored for insect attack as part of a management regime with one follow up insecticide application in year 1. See Table A2.1 for damage scenario details.

Management Scenario 1*Description*

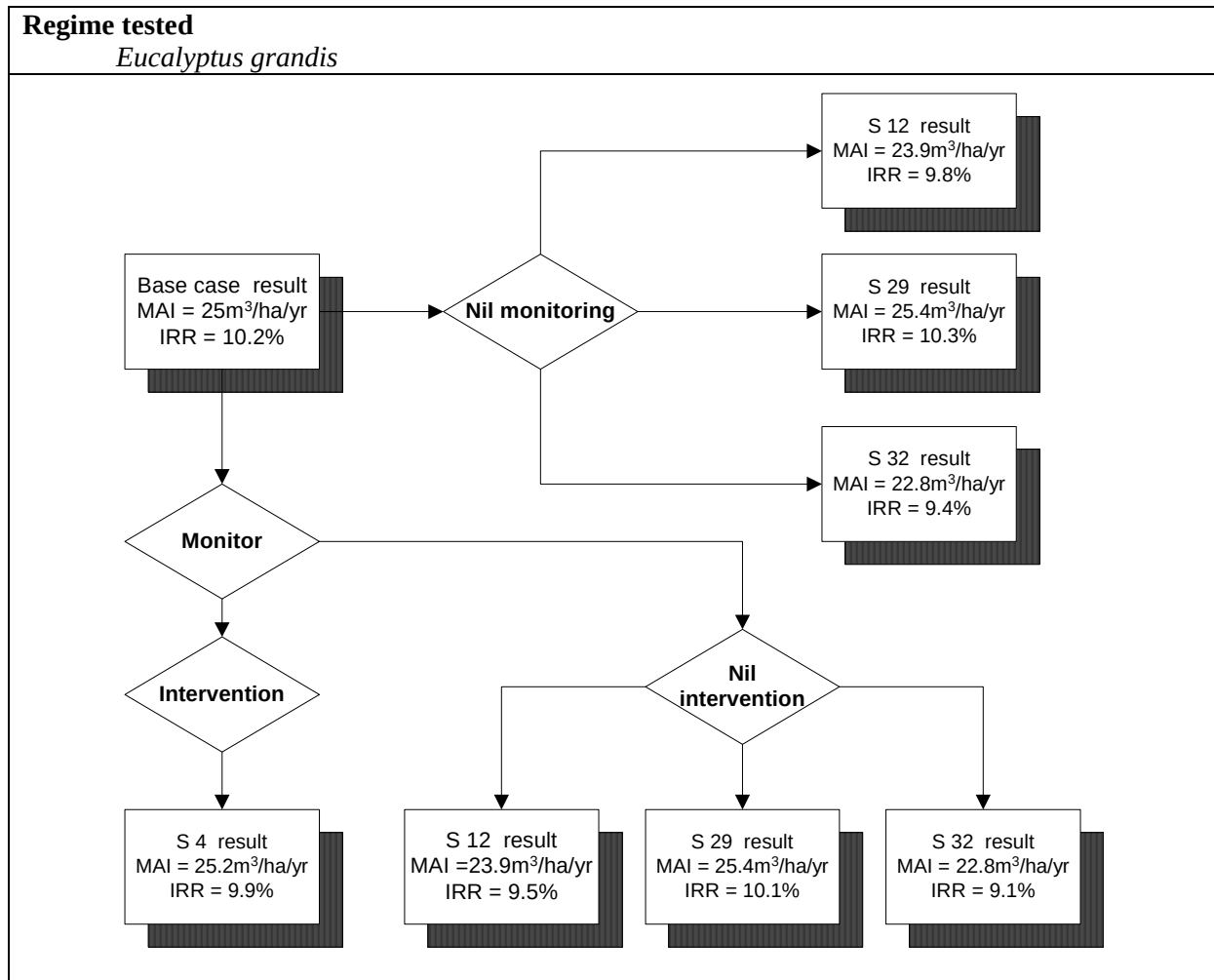
- 30% defoliation in late summer of year 1(S 4)
- followed by up to 80% defoliation early summer in the same year (S 12)
- with light defoliation continued each year up to year 4 (S 29)
- OR that defoliation does not commence till year 3, when the trees receive a light defoliation in early summer, followed by a heavy defoliation in late summer (S 32)

*Comparison to base case*

If the manager decides not to monitor the plantations, there is a

- risk that up to 17% of productivity is lost, and with that,
- IRR is reduced by 37%.

for a small loss of IRR, the extra cost of monitoring could avert losses by identifying the need to spray.



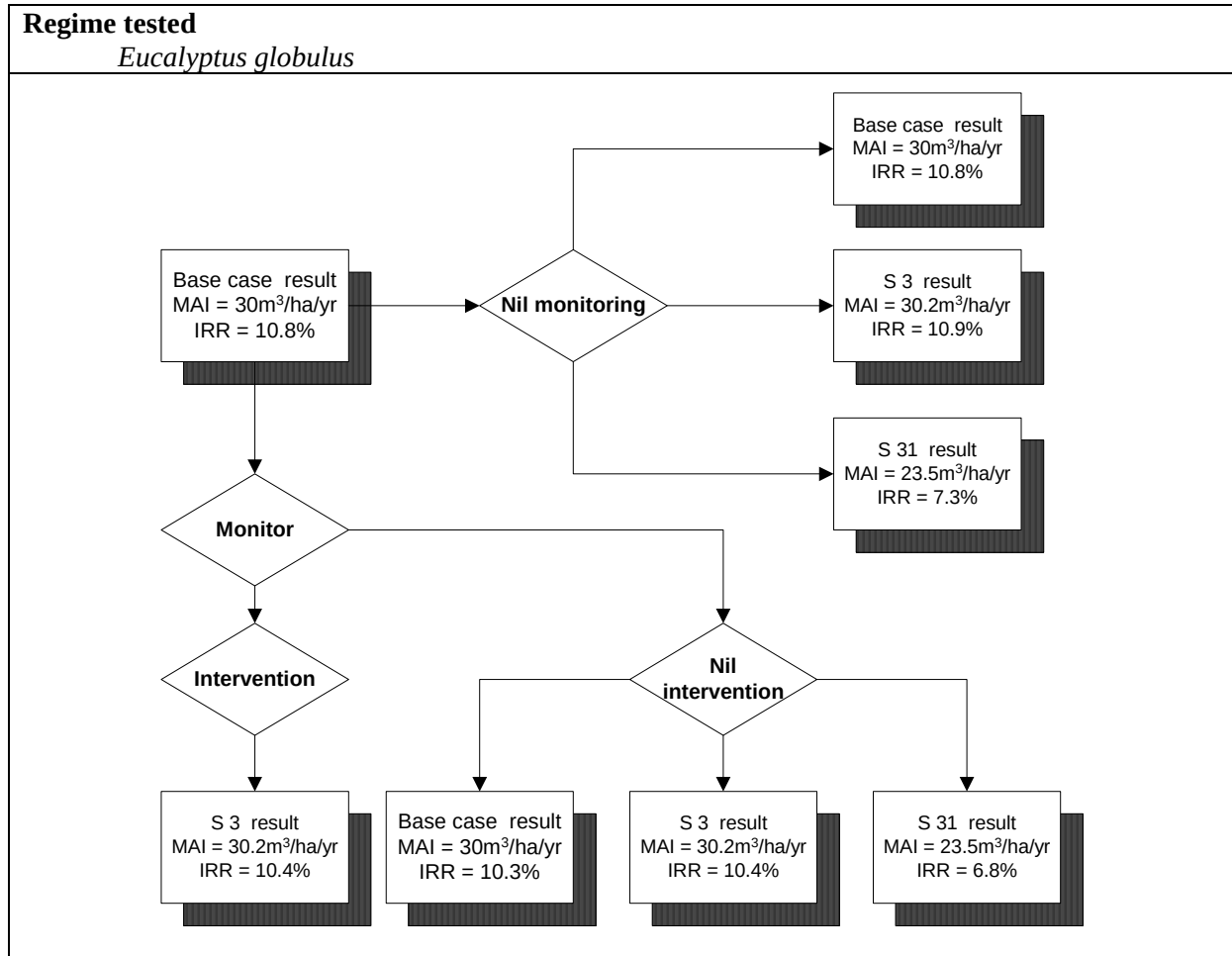
Comparison to base case

If the manager decides not to monitor the plantations,

- there is a risk that up to 8% of productivity is lost, and with that,
- IRR is reduced by 11%.
- The *E. grandis* plantation regime is more robust compared to the *E. globulus* plantation regime, with less risk (as measured by the impact of decisions).

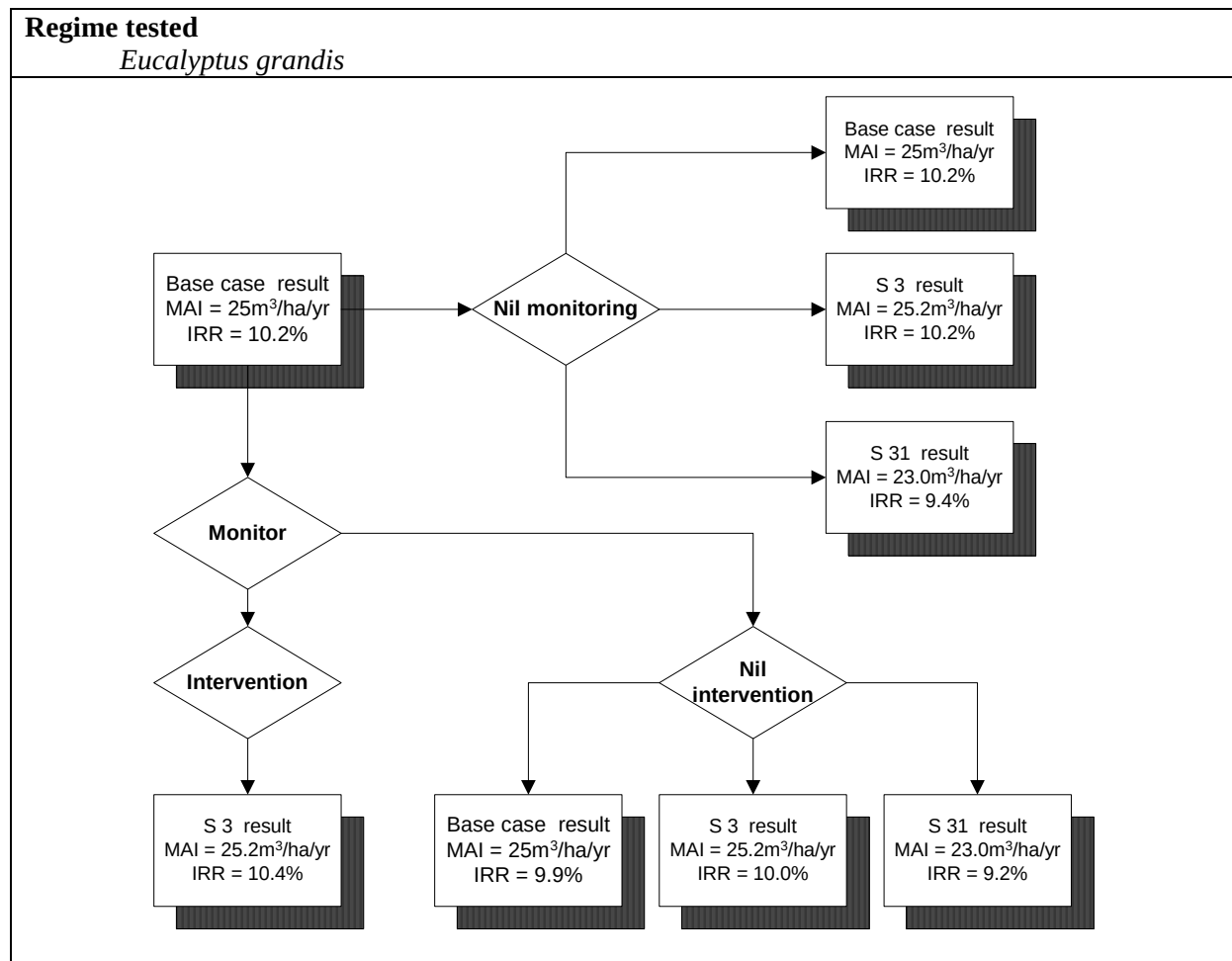
Management Scenario 2*Description*

- up to 30% defoliation occurs in early summer of year 1 (S 3);
- followed by up to 80% defoliation in late summer (S 31).

*Comparison to base case*

If the manager decides not to monitor the plantations, there is

- a risk that up to 22% of productivity is lost, and with that,
- IRR is reduced by 37%.



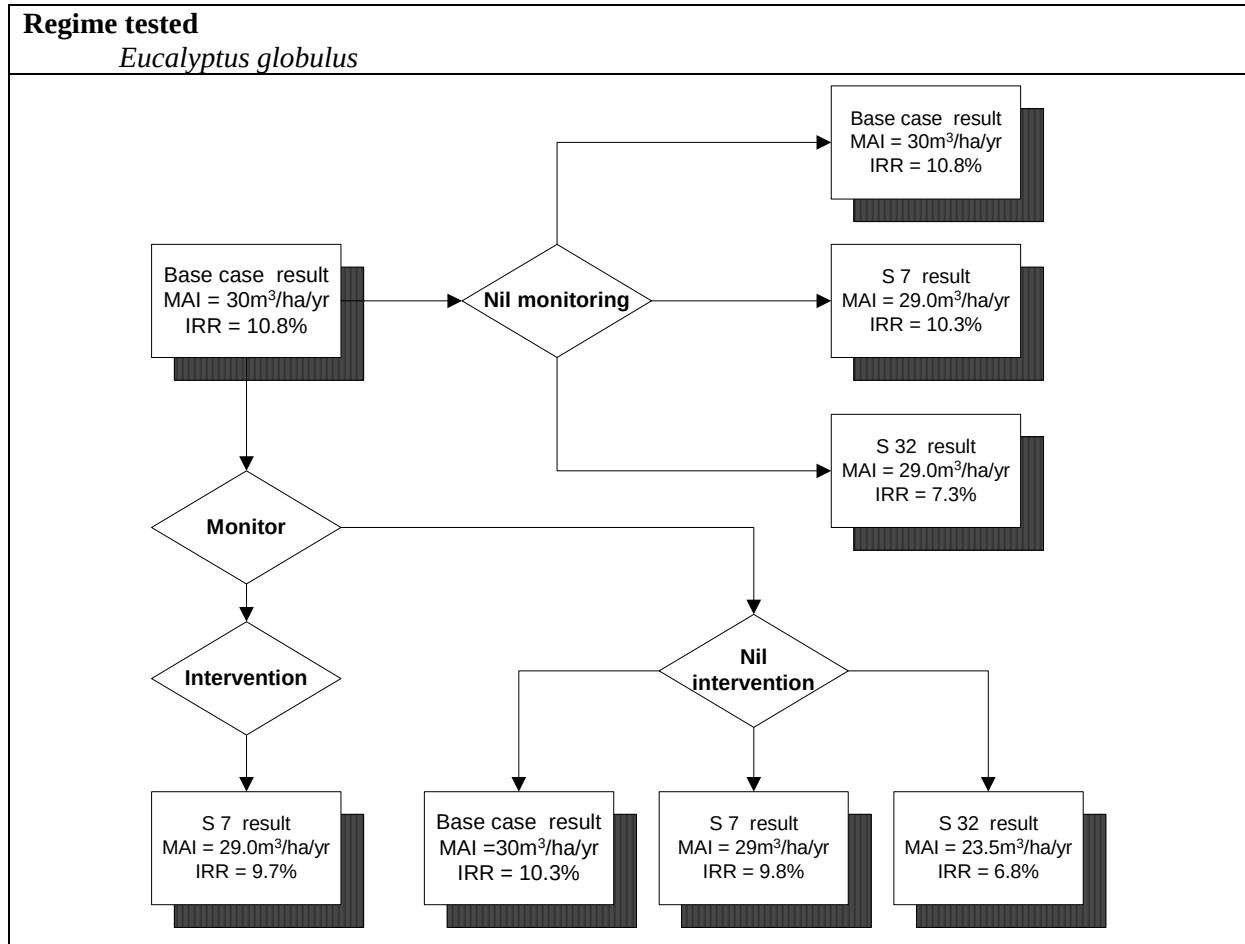
Comparison to base case

If the manager decides not to monitor the plantations, there is

- a risk that up to 8% of productivity is lost, and with that,
- IRR is reduced by 10%.
- The *E. grandis* plantation regime is more robust compared to the *E. globulus* plantation regime, with less risk (as measured by the impact of decisions).

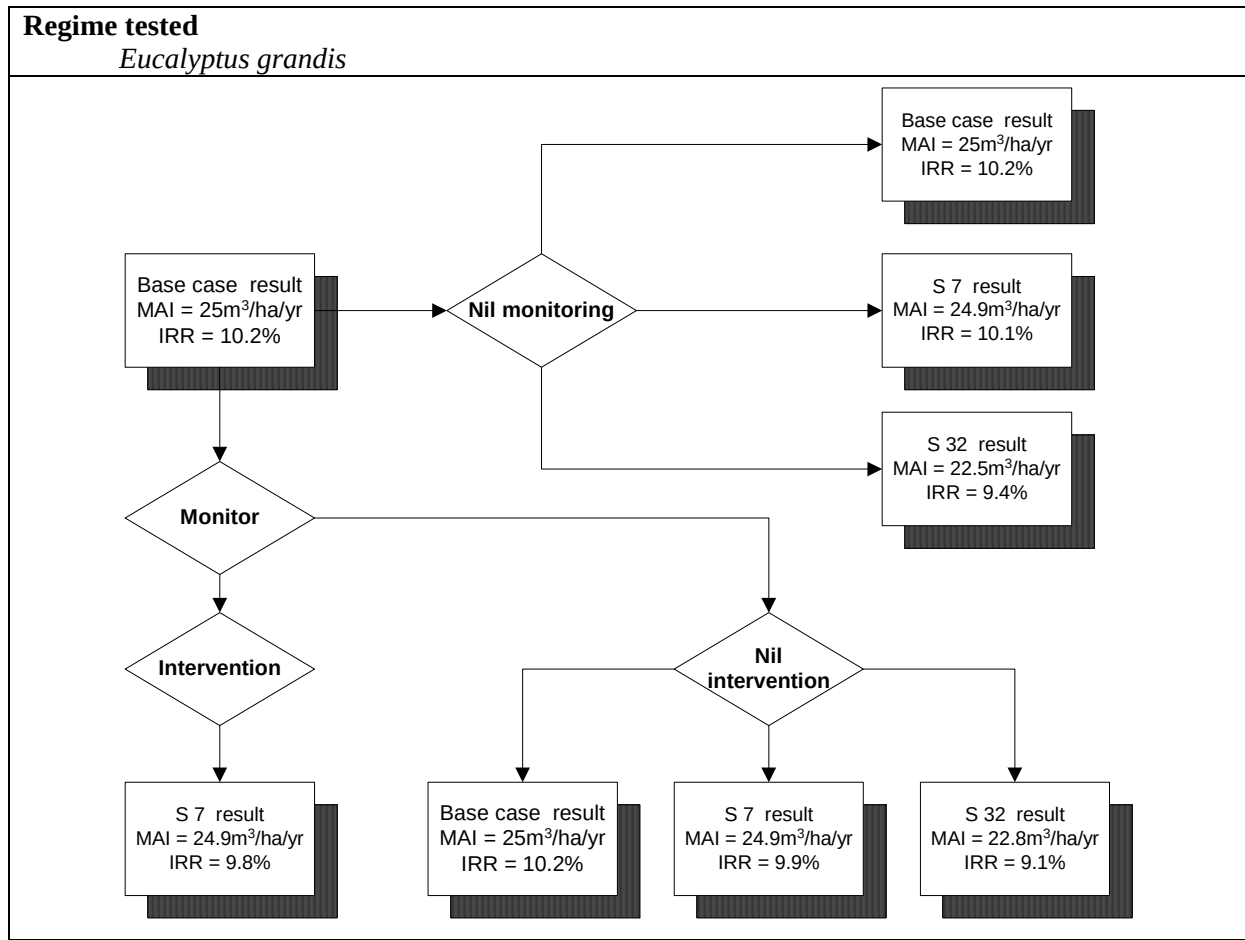
Management Scenario 3*Description*

- up to 30% defoliation occurs in early summer of year 3 (S 7);
- with insect attack continuing in late summer with up to 80% defoliation (S 32).

*Comparison to base case*

If the manager decides not to monitor the plantations, there is

- a risk that up to 22% of productivity is lost, and with that,
- IRR is reduced by 37%.



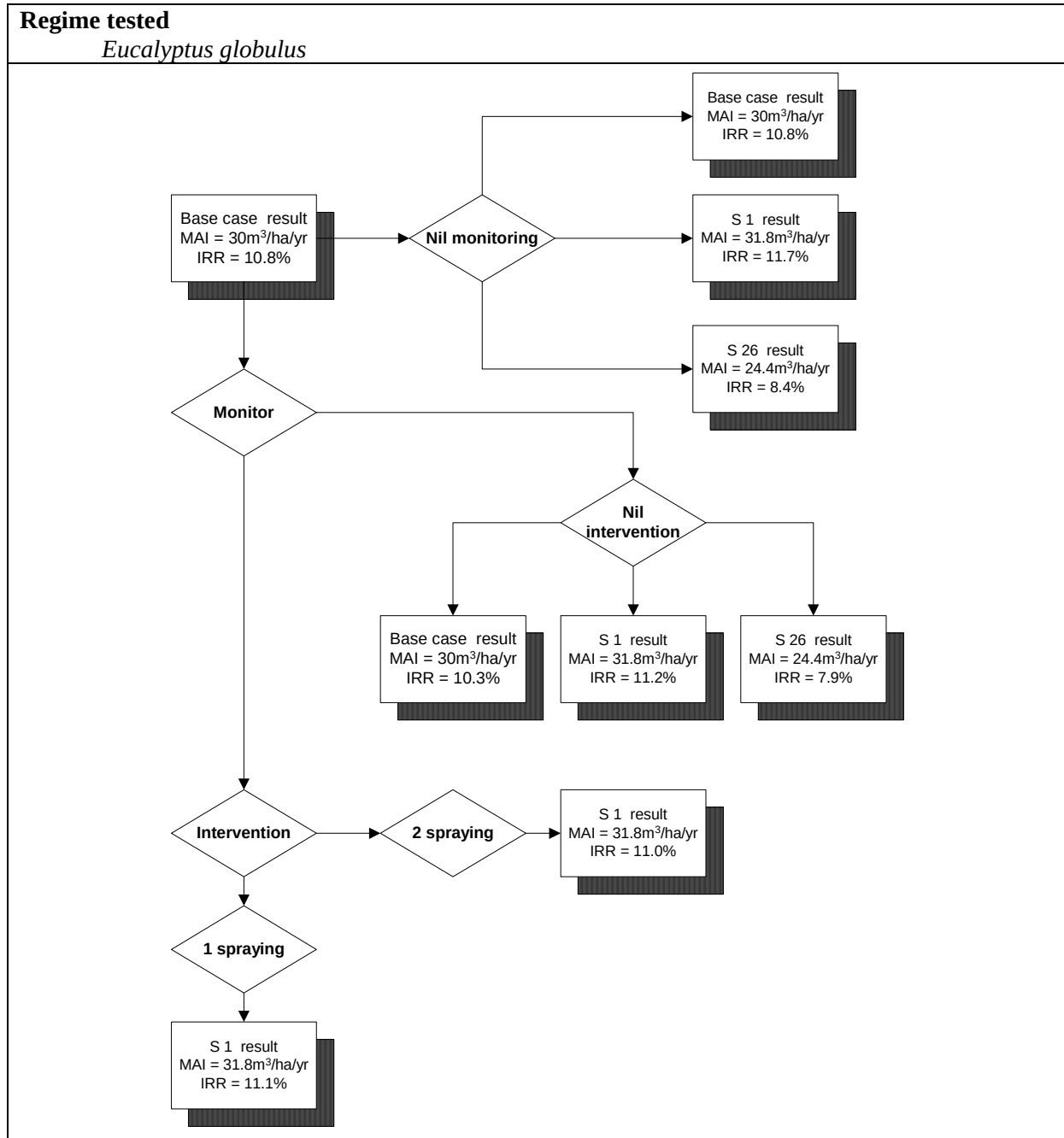
Comparison to base case

If the manager decides not to monitor the plantations, there is

- a risk that up to 13% of productivity is lost, and with that,
- IRR is reduced by 11%.
- The *E. grandis* plantation regime is more robust compared to the *E. globulus* plantation regime, with less risk (as measured by the impact of decisions).

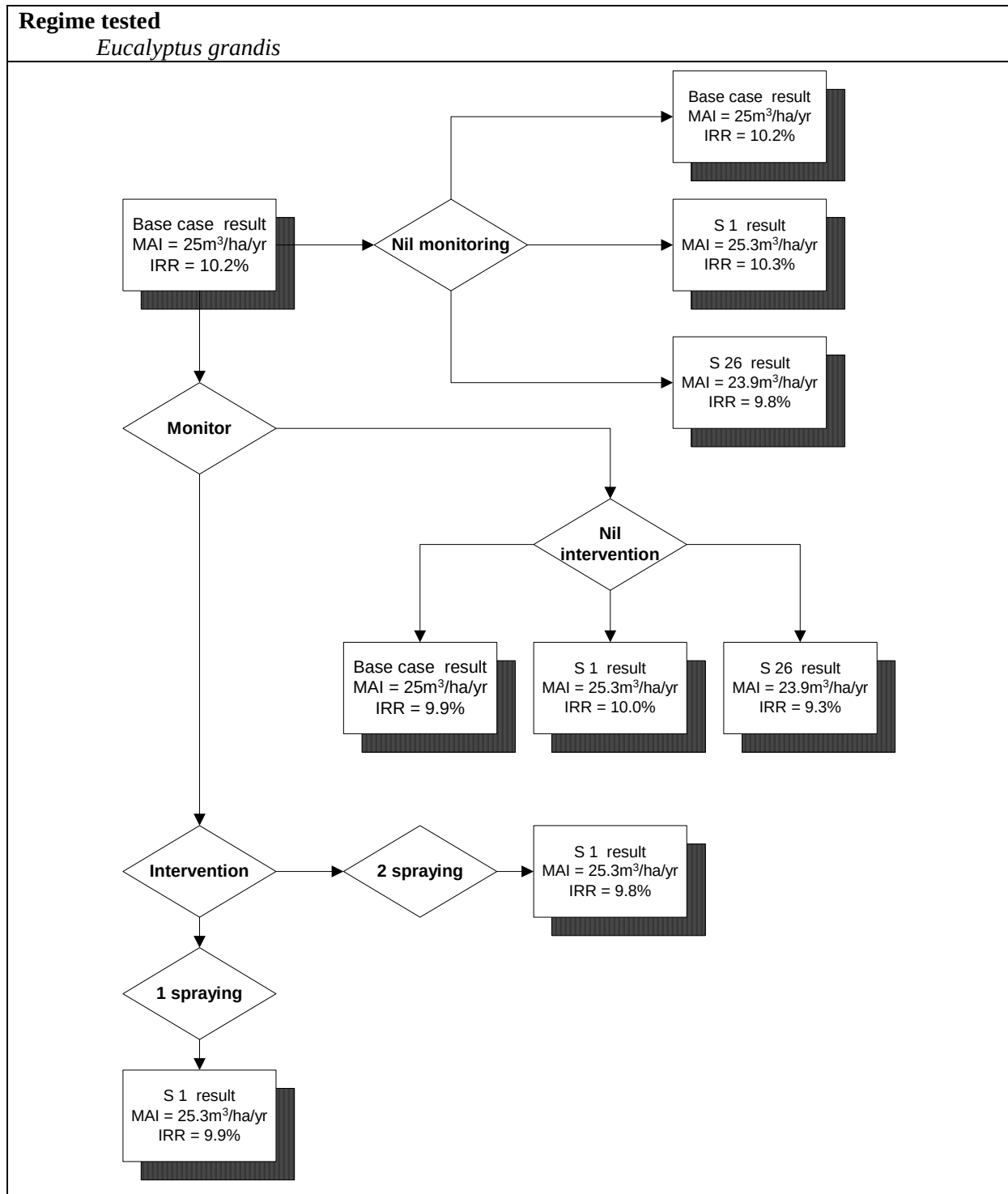
Management Scenario 4*Description*

- up to 30% defoliation in winter of year 1 (S 1);
- with up to 100% defoliation occurring in winter of year 2 (S 26);

*Comparison to base case*

If the manager decides not to monitor the plantations, there is

- a risk that up to 17% of productivity is lost, and with that,
- IRR is reduced by 27%.



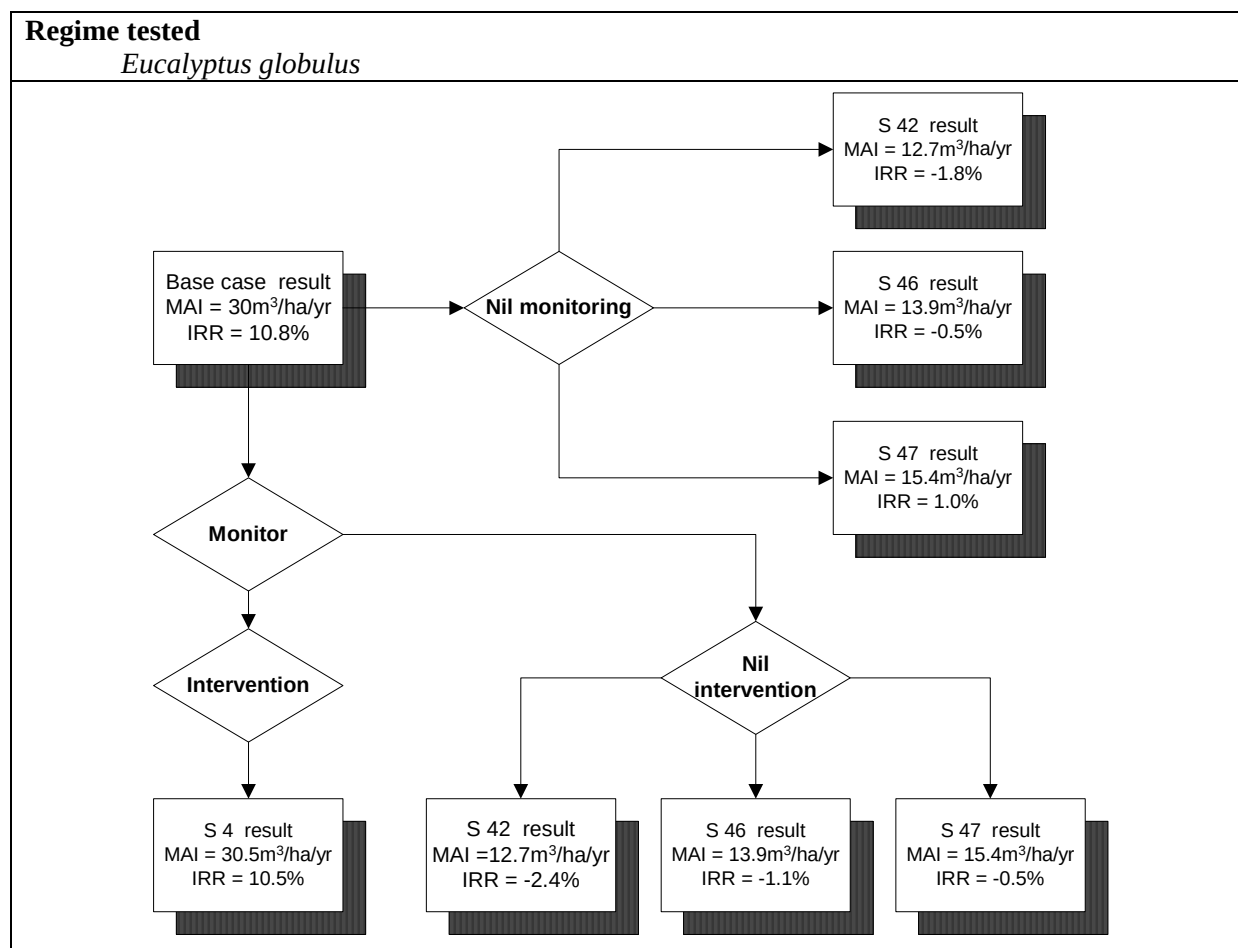
Comparison to base case

If the manager decides not to monitor the plantations, there is

- a risk that up to 4% of productivity is lost, and with that,
- IRR is reduced by 9%.
- The *E. grandis* plantation regime is more robust compared to the *E. globulus* plantation regime, with less risk (as measured by the impact of decisions).

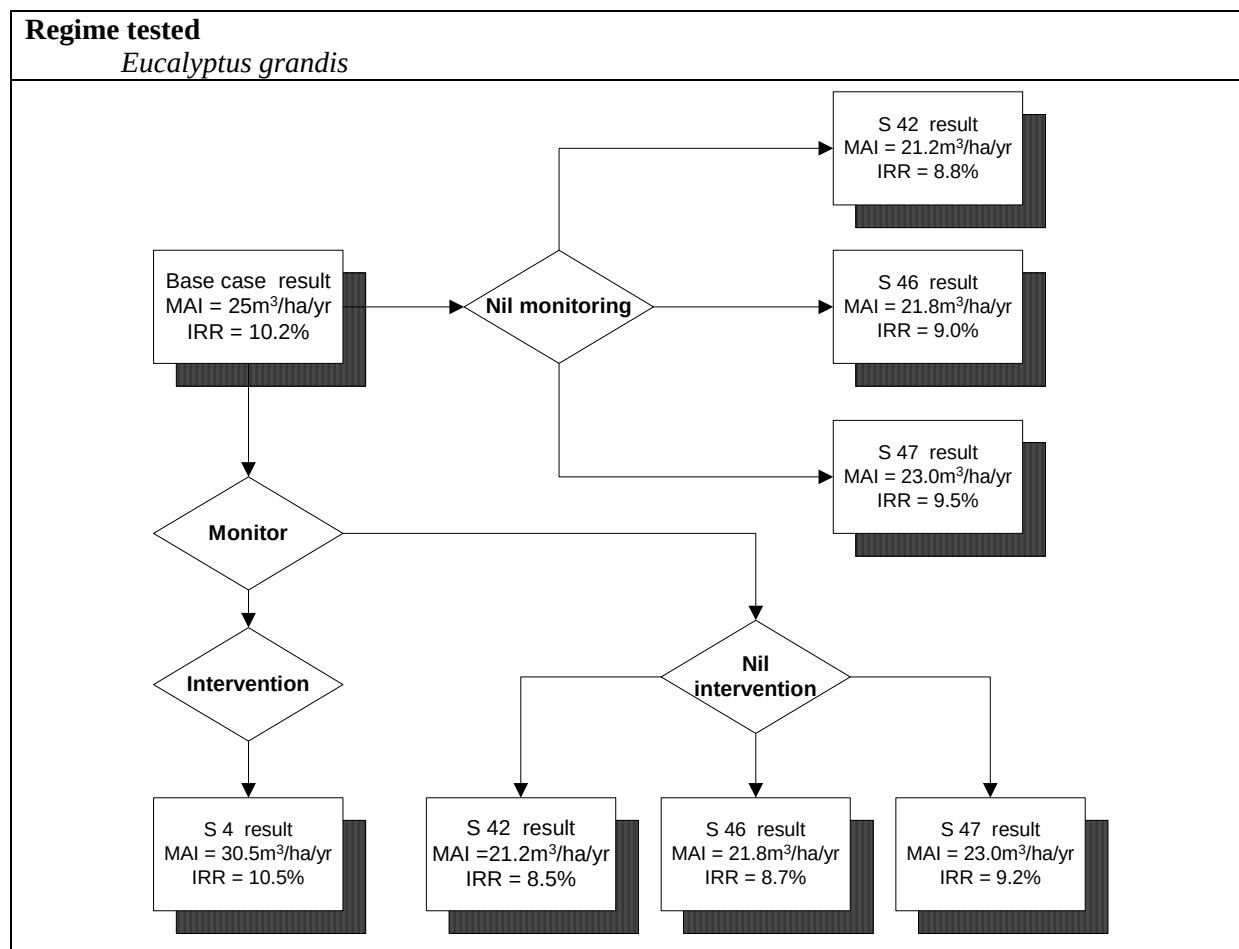
Management Scenario 5*Description*

- an outbreak (100% defoliation) occurs in winters of year 2 and 3 (S 42);
- OR an outbreak (100% defoliation) occurs in the winter of year 2 and 5 (S 46);
- OR an outbreak (100% defoliation) occurs in the winter of year 2 and 9 (S 47).

*Comparison to base case*

If the manager decides not to monitor the plantations, there is

- a risk that up to 58% of productivity is lost, and with that, IRR is reduced by 122%.



Comparison to base case

If the manager decides not to monitor the plantations, there is

- a risk that up to 15% of productivity is lost, and with that,
- IRR is reduced by 17%.
- The *E. grandis* plantation regime is more robust compared to the *E. globulus* plantation regime, with less risk (as measured by the impact of decisions).

Discussion

Source–sink plant growth model

While the plant growth model is still in its early phases of development, we believe it adequately describes how a eucalypt tree grows. By considering allocation of stored carbohydrates for growth and mechanisms of compensation after defoliation, it provides clear insight into how defoliation affects growth. The model is very flexible and can be extended to deal with other forms of damage apart from defoliation. For example, by changing where the tree loses carbon (leaves vs. carbohydrate pool or growing shoots) it could be extended to study effects of the non-defoliation damage of sap sucking insects.

Data from the insecticide exclusion treatments were used to adjust the model tree to show realistic growth patterns without defoliation. The data on growth of defoliated trees obtained in the trials were

used to help calibrate parameters for compensatory growth in the model. Using field data to calibrate the model helped overcome the paucity of data on some critical functions and it gives confidence that the model is a fair representation of the growth of a eucalypt tree.

The use of field data to calibrate the model does have its limits, however. The single most important hindrance to improving the model is the paucity of data in several critical areas of eucalypt growth and development that the model attempts to describe. To address these limitations and to generally improve the performance of the model, data are needed on:

- *Biomass of different plant parts measured annually or biannually.* No such data seem to exist for eucalypts. For the model we used published data on *P. radiata* (International Greenhouse Partnerships Office 2001). There was some unpublished data indicating that the pattern of biomass allocation is reasonably constant across species (EucProd conference in Hobart, Nov 2002) but that the pattern of biomass allocation changes with the environmental conditions (e.g. changes in root/shoot ratio).
- *Seasonal changes in biomass allocation to different plant parts.* No data exist, except that we have some unpublished observations on timing of new leaf production.
- *Effects of thinning on changes in biomass allocation to different parts.* After thinning, trees are expected to allocate more carbon to branches to spread the canopy, but we did not have the data to quantify such changes in eucalypts. In the model, we did not deal with the tree architecture because of the lack of data.
- *Effects of herbivory on changes in biomass allocation to different parts.* Again, there seems to be no data on this, although this was one of the three mechanisms of compensation incorporated in the model.
- *Effects of fertilisation/irrigation on changes in biomass allocation to different parts.* In the model, irrigated trees keep producing leaves in February and March, but non-irrigated trees do not produce new leaves in those two months.
- *Ontogenetic change in biomass allocation to different parts.* We could not find any data on ontogenetic changes, but they are critical to the model.
- *Stored carbon.* There is no data on carbohydrate storage in eucalypts. This is another critical determinate of compensatory growth responses.
- *Mechanisms of compensation.* We have very little data on how eucalypts respond to loss of leaf biomass.

Paucity of data for the above list of topics seems to apply to all eucalypts. Even with *E. globulus*, *E. camaldulensis*, and *E. grandis*, which probably are the most studied eucalypts, there seems to be little information about storage and biomass allocation. The core of the model is the allocation pattern and the way the pattern changes due to various causes, such as insect damage). The best way to improve the model is to learn more about allocation patterns.

In summary then:

- Model strengths:
 1. Incorporates carbohydrate allocation pattern (other models have very simple rules of allocation.)
 2. Incorporates stored carbon (No other model has this component.)
 3. Incorporates three mechanisms of compensation (No other model has this component.)

- Model weaknesses:
 1. Lack of data on allocation patterns.
 2. The model has not been formally validated.

Sylva Ento Model

The *Sylva Ento Model* was developed based on a dynamic discussion of inputs and desired model abilities. It aimed to be able to apply economic analysis to insect damage scenarios as impacting on a series of plantation management regimes.

The *Sylva Ento Model* brings together a wide range of plantation tree and wood attributes information. A range of assumptions and best estimates were used in the absence of more complete information. A key factor is that the source-sink model of plant growth is separate and external to the *Sylva Ento Model*. There is potential to more completely link the two models if it becomes appropriate. For the assumptions made in the conversion of the source-sink model data (dry weight of support tissue) to volume, better information and preferably relationships between tree age and the attribute of interest are required. These include:

- The ratio of support tissue to stem wood. The allocation of biomass to different tree components as used in some carbon accounting is based on conifer species (i.e. International Greenhouse Partnerships Office (2001)). It was felt preferable to use eucalypt, rather than conifer data, even in the absence of complete time series data. The relationships used in the model were based on a number of plantation grown eucalypt species (Bradstock 1981; Christie and Button 1991; Frederick *et al.* 1985a; Frederick *et al.* 1985b; International Greenhouse Partnerships Office 2001). Based on field observations, the ratio will be affected by management practises i.e. thinning and spacing, tree species and site.
- The relationship between basic density and age. The relationship used in the model was for *E. globulus* based on published data (Borrallho *et al.* 1993; Dean *et al.* 1990; Downes *et al.* 1997; Hicks and Clark 2001; Ilic *et al.* 2000; Kibblewhite *et al.* 2001; Northway and Blakemore 2001; Phillips 1988; Raymond and Muneri 2001; Tibbits *et al.* 1990; Whiteman 1997; Williams 1994; Yang and Waugh 1996). It was not possible to access time series data with uniform management, genetics and site.
- The need to calibrate the *Sylva Ento Model* against the source-sink model base run data should be eliminated. This can be done by either combining the models or by addressing the issues raised in the above.

In summary then:

- Model strengths:
 1. Give a broad range of management options and generates outcomes.
 2. It has a high degree of flexibility.
- Model weaknesses:
 1. Some of the key inputs are based on incomplete data.
 2. The model has not been formally validated.

Plantation management regimes

As a desk top study (with only one site inspection in the Murray Valley), the purpose of this work was to explore the issues based on realistic plantation regimes. It has provided an indication of the available data, information and knowledge, and has stimulated consideration of a range of important issues associated with insect management in eucalypt plantations.

Two detailed irrigated plantation management regimes were modelled: *E. globulus* for pulpwood production and *E. grandis* for solid wood products. In both cases, there has not been an actual plantation managed as assumed through to rotation in the study area. In fact, we assumed that processing of the sawlogs and veneer logs, occurs in Shepparton, and that the woodchips and pulplogs are transported by rail to Geelong, neither of which currently occurs. It must be stated that the proposed regimes and markets are realistic and are possible give a critical resource mass. The plantation management regimes, market options (including price) were based on industry experience, overseas operations, and local knowledge. It was felt that the exercise was to test insect management, based on realistic (and not necessarily actual) plantation regimes. In practice, the full effect of irrigation, site and management are not fully understood.

Yield tables (volume per age) for the species of interest were not available. Based on local knowledge, industry experience and overseas operations, expected MAI for each plantation regime was determined. In order to generate a yield table, the yield table for *E. globulus* growing in Victoria (Wong *et al.* 2000) was shifted up or down by a set percentage to result in the desired MAI. This could be improved with species and management specific yield tables, but in the interim, provided a useful solution.

Damage scenarios

Due to the nature of the plant growth model it was not possible to accurately simulate species specific details of insect damage. It was possible, however, to design scenarios to reflect the general patterns of damage observed for specific insects. So for example, winter damage scenarios were designed to simulate autumn gum moth (*Mnesampela privata* (Guenée) (Lepidoptera: Geometridae)) damage dynamics, with low levels of damage initially appearing in March and building to a peak in late June to early July (see Chapters 2–4, this report). Spring damage patterns are similar to those seen in winter, with damage levels building up over the season, although at a faster rate than in winter (see Chapter 2, this report). Therefore, spring damage scenarios built from low levels in September to a peak in November. For winter and spring defoliation, sigmoidal equations were used to simulate the pattern of damage build up over the season. This was necessary as field data was not available for the range of damage levels need for the simulations. Equation parameters were fitted using field data (see Chapters 2–4, this report), with damage increasing in monthly increments to match the inputs for the source-sink model.

Summer damage scenarios were designed to simulate the dynamics of various leaf feeding beetles such as Christmas beetle (*Anoplognathus* spp. (Coleoptera: Scarabaeidae)) (see Chapters 4–5, this report) and leaf beetles (e.g. *Paropsis atomaria* Olivier (Coleoptera: Chrysomelidae)) (Collett and Neumann 2002). The common leaf feeding species that occur in plantations over summer are generally multivoltine (Collett and Neumann 2002) and two damage peaks were simulated, one in early summer (December) and one in late summer (February).

It should be noted that the only type of insect damage applied to the source-sink model was that resulting in leaf loss (i.e. defoliation). We did not simulate damage to other plant parts such as that by wood borers or root feeders, or damage in addition to defoliation by sucking insects (e.g. pathogen transmission, changes in photosynthetic sinks and water stress). While the plant model has the capacity to simulate non-leaf damage, there were not sufficient data to calibrate it for such responses. We also assumed that the susceptibility of trees to attack was not altered by previous damage episodes.

Tree vigour is a factor in determining the impact of insect damage on eucalypts (Collett and Neumann 2002), but there was insufficient data to calibrate the model to show such responses.

It was not appropriate to apply all damage scenarios to all plantation regimes. While autumn gum moth damage to *E. globulus* is restricted to juvenile foliage and hence to trees prior to canopy closure, under certain conditions the insect can outbreak on mature *E. grandis* plantations where trees are 4–5 year old (see Chapter 2, this report). Such information determined what defoliation scenarios were applied to plantation regimes.

Basis of economic analysis

It is important to discuss the method of economic evaluation of the plantation regimes and damage scenarios. Two broad options can be used: net present value (NPV) or internal rate of return (IRR).

In NPV analysis, all cash flows are brought to a common base or present value (PV) by application of a discount factor. PV is defined as the “the discounted value of a financial sum arising at some future period” (Bannock *et al.* 1992). If the cash outflow and cash inflows are both discounted and summed, the result is the NPV of that cash flow. Discount factors are calculated based on an assumed discount rate. A discount rate is effectively a measure of the time value of money and the required return for deferred consumption of funds now, till some future point in time. Discount rates are expressed as a percentage rate. Due to the nature of NPV requiring selection of a discount rate, the outcome is dependent on the discount rate choice made. A low discount rate gives as much weight in the analysis to future cash flows and a higher discount rate gives more weight to the early cash flows. Discount rates can be based on the risk free interest rate (i.e. a government bond over a similar time frame), plus a risk premium based on the nature of the project under assessment. As a guide to discount rate selection, if the techniques used in the valuation of forestry assets are considered, there is not a clear guide as to how to select discount rates. AAS35 Self-generating and Regenerating Assets (Australian Accounting Standard 1998) states that “the discount rate used to discount the cash flows needs to be consistent with the measurement of the cash flows to be discounted”.

Internal rate of return (IRR) is defined as the “the rate of interest which discounts the flows over time of the net revenue generated by an investment such that the PV of that net revenue flow is equal to the capital sum invested” (Bannock *et al.* 1992). In more simple terms, if you were to place all cash outflows otherwise to be invested in a plantation into a “bank”, and after a set period of time (i.e. when the plantation was to be harvested) withdrew all the funds deposited and the interest earned, and calculated the compound interest rate, that would be the same as the IRR for that cash flow stream. (Compound interest includes the interest earned on interest.) A significant advantage is that the determined IRR is a fixed point and it is not dependent on a selected discount rate. It is important to note, that unless cash flows have been adjusted for anticipated inflation, that the determined IRR is a real interest rate or increase in true consumption potential.

Once a broad approach to economic analysis has been decided, the basis of the analysis must be selected. de Little (2002) presents an analysis of the cost/benefit of insect control in a Tasmanian plantation. The author takes the approach of using the cost of monitoring and insect control and the value of the pulpwood “saved” to generate NPV and IRR. Montague (1996) takes a similar approach with an analysis of the cost–benefit of browsing animal control. If the wood “saved” was extra, it would be a marginal increase on an unchanged base volume, and marginal costs and returns analysis would be appropriate in determining the impact of such management interventions (a management question would be “is it a good investment decision to spend the extra funds, to generate the extra wood?”). For example, Dell *et al.* (2001), show that there is an increase in the standing volume of a *Eucalyptus urophylla* S.T.Blake plantation (in China) with additional phosphorous application, with the increase slowing at higher application rates (at some point extra fertiliser will have a toxic effect). The cost-benefit of the extra phosphorous could be determined, and a decision made. A point of context is needed. Ferguson (1993) states that trees are unlike other capital investments in that the

factory and the product are the same thing. If we extrapolate this concept, then extra fertiliser is additional raw material allowing an increase in factory production, were as insect damage (defoliation) reduces the factories ability to produce by reducing the factory asset. A defoliated tree will need to expend energy to repair the damage done. Insect damage is generally a negative, in that it results in a loss (although there is the potential for the trees to over compensate and produce more biomass). Any management action should aim to reduce the impact of such damage. In some cases, it may be the best outcome financially to accept a physical loss, rather than attempt to reduce the loss by the extra expense of management intervention.

As a comparison, consider management scenario 5 (Table 7.2) for *E. globulus*. The worst case option is a change in MAI from the base case 30m³/ha/yr to 12.7m³/ha/yr (a loss of 58%) with damage scenario S 42. This represents a loss of 173m³/ha at rotation. Taking a marginal analysis approach, monitoring and one insect control intervention would result in preventing significant damage (resulting in outcomes for S 4). Based on the cost of “saving” wood production, the IRR of the insect control would be 57%. This would be a very good investment if the underlying analysis assumptions were correct. If the full plantation cost cycle is considered, the actual result of the insect management intervention is a change in IRR from 10.8% (base case) to 10.5%. The approach can be more broadly applied. If an analysis of the effect of insect defoliation on windbreaks was to be undertaken, it should include the full costs and savings, and not just be the lost production units times a gross margin for that agricultural commodity as a measure of the returns of the insect control.

Therefore, economic analysis of insect (and other damage agents such as browsers) cannot be undertaken on a marginal basis, but rather must consider the full plantation cost cycle.

The boundary of economic analysis must be determined. Does the analysis consider all the multiplier effects (i.e. the extra benefit of expenditure to the broader community or, for every dollar invested in plantation development, the money going round in the community has the impact of a greater sum of money) or not? In the case of the analysis used, it does not include the multiplier effect of the extra funds expended in insect control. Does the analysis consider the externalities of the operation? Externalities are defined as spill over costs or benefits, unintended consequences, or unintended side effects (either beneficial or detrimental) associated with a market transaction (Khan 1998). While the externalities of insect management are not considered in the analysis, they warrant some discussion. The externalities of insect control can be very direct (i.e. off target damage to an adjacent property) or perhaps a bit more subtle, but none the less with a significant impact (i.e. destruction of natural enemy populations). Good management of insecticide application can reduce the risk of off target damage. Phillips (1996) outlines a range of beneficial natural enemy insects, including their mode of action and effect. Selection of appropriate insecticides can reduce the impact on natural enemies/non target insects (i.e. the use of *Bacillus thuringiensis* based products, (Clare and O’Callaghan 2000)). A manager needs to consider this issue, because if the local population of beneficial predators is reduced or eliminated, then the pest insect population may be more likely to reach outbreak levels and cause significant damage, and / or lock plantation managers into a must spray situation.

Plantation productivity

In the absence of insect attack that damages the likely commercial products from plantations, it is the impact on MAI that is critical (i.e. a boring insect may reduce sawlog quality trees to pulp wood only). Abbott and Wills (1996) found that 50% artificial defoliation of *E. globulus* had only a minor effect on tree growth after 12 months. Increase in MAI associated with insect defoliation is reported by Elliott *et al.* (1998). Wickman (1980) in Elliott *et al.* (1998) stated “that an outbreak of defoliating insects can reduce the increment of individual trees in the short term but increase MAI of the whole stand over the longer term. This can occur through the outbreak causing the death of some individual tree and the residual trees eventually increasing their growth due to a thinning effect.” This effect explains the better recovery of the *E. grandis* plantation due to the combined effect of time and thinning. It may also explain part of the poor recovery in the *E. globulus* plantation regime.

A tree's capacity to respond and recover from defoliation will be influenced by other management practices. If weed control remains adequate, the trees will have the greatest chance of recovery from insect attack.

A positive impact of light levels of defoliation may indicate that management intervention (i.e. spraying) is not required (and if done would adversely impact on IRR by increasing the cost of production). It could be that natural enemies are keeping the pest insect in check, and that unwarranted spraying would disrupt that balance. A "do nothing" approach may be appropriate if the manager was confident that the observed light defoliation would not escalate into a more significant outbreak, and if it was to escalate, that the trigger points for intervention are well understood. It is therefore critical that the manager understands the insect pest biology and monitors the population.

Plantation management

Management pressures

In order to put plantation management into context, it is important to define management and investment. Management is defined by Robbins (1991) as: "The process of getting activities completed efficiently with and through other people". Investment is defined as: "real capital formation, such as the production or maintenance of machinery.....Investment involves the sacrifice of current consumption and the production of investment goods which are used to produce commodities" (Bannock *et al.* 1992).

A plantation manager could find themselves under different pressures depending on how directly or close the investors for whom they are managing plantations, are to the actual plantations. For example, a manager of a plantation owned and managed as a raw material production centre for an industrial processor will have greater autonomy compared to a manager establishing trees for a land owner. The industrial processor would employ management to deliver wood, and have little input into day to day operations. A landowner could have a more hands on approach as they would (should) regularly inspect the plantation. Where the manager is growing trees on behalf of investors (i.e. under a managed investment scheme), the investors may inspect the plantation and would want to see that their investment is safe (the likely returns from their investment will depend on how well risk is managed in the plantation). In regard to insect pest management, defoliation where apparent, may alarm the investor as they perceive it to be a sign of increased risk to their investment. A plantation manager may be under increased and in some cases, unnecessary pressure to ensure that the plantation "looks good". If inspected, investors considering *E. globulus* management scenario 1, and a series of light defoliations (S 29), may be alarmed and insist on intervention. If the insect was not likely to escalate up to outbreak (and S 32), then insect control may not have been warranted, as the nil intervention with monitoring outcome only changes IRR from 10.8% to 10.2%. If considering the other elements of the triple bottom line, the loss of IRR may become an acceptable outcome.

A "cheap" option

Currently the cost of insect control is relatively cheap compared to other plantation management inputs. This may make a manager more likely to take this option, particularly in light of pressures discussed above. It may be that a manager does not monitor, but rather automatically sprays. A manager should consider the risk inherent in such an approach. If an automatic spray options is taken, without the use of selective insecticides, the manager may effectively remove all insects, both beneficial and pest from the plantations. (There may be the potential for beneficial insects to remain in retained native vegetation.) The manager may be effectively locked into such a management regime. This may be acceptable if the management options (insecticides and application techniques) remain unchanged.

Insecticide option and/or restriction of application methods could place added cost pressure on the plantation. It could be that due to public pressure (i.e. proximity to other land uses), a significant mishap, information from overseas, or some other reason, that aerial application could be restricted. Considering management scenario 3 for *E. globulus* (S 7—early summer 30% defoliation at age 3 years), the manager may choose to spray or not. If the manager chooses not to spray (S 32) and the defoliation of 80% results in late summer, IRR will go from 10.8% to 6.8% (a loss of 37%) with monitoring. If control is with fixed wing application at \$20/ha (based on an experienced aerial contractor (Blyth 2002)), and is successful in controlling the insect pest, then IRR goes from 10.8% to 9.7% (a loss of 10.2%). If application is by helicopter at a cost of \$45/ha (based on de Little (2002)), then IRR goes from 10.8% to 9.6% (a loss of 11%). As shown, even when aerial application cost is more than doubled (from \$20/ha to \$45), there is little impact on IRR with (9.7% to 9.6%). At age 3 (as per management scenario 3), plantation grown eucalypts are likely to be well over 7–8m tall. At this stage, it would be marginal whether or not an insect pest could be effectively treated from the ground. If insecticides could be applied from the ground at \$90/ha, application (Lawrence 2002), it would reduce IRR to 9.4%. Again, this is not a large change in returns. Where the trees are too tall for ground based spraying, stem injection may be an option. Assuming application costs of \$100/ha with 1000 stems/ha, and insecticide costs of \$20/ha, this will reduce IRR to 9.4%. In summary, with insect control ranging from \$20/ha through to \$120/ha, IRR goes from 9.7% to 9.4%

Even if returns are not sensitive to insecticide application costs, there is an important consideration. Aerial application of insecticides is very quick. Based on fixed wing application to broad acres, given the right conditions, 120 to 150ha/hr/plane can be treated. Ground based application could treat between 1 and 2 ha/hr/unit. Ground based stem injection could treat approximately 0.6ha/hr/person. Therefore, depending on the labour force and equipment available, any ground based operation would be much slower than an aerial operation, and given the short time between early summer and later summer as in management scenario 3, may be ineffective in reducing defoliation. Therefore, it is critical that the option to used aerial application of insecticides is retained and used appropriately.

IPM and monitoring

Plantation managers can choose to take a proactive, or a more hands off approach, to management. Proactive pest management can include an Integrated Pest Management (IPM) system, where management actively seeks to understand the insect pest risk, monitor populations and respond at the most appropriate point in the pest damage/life cycle. Elliott *et al.* (1992) presents an IPM system for *Chrysophtharta bimaculata* Olivier (Coleoptera: Chrysomelidae) (Tasmanian eucalypt leaf beetle) which includes population monitoring, an understanding of when best to treat and at what stage the pest insect is vulnerable to predatory insects, and control options. Steinbauer and Floyd (2000) present a system of risk assessment for autumn gum moth that allows the manager to rate the risk for discrete plantation areas. The aim is to focus attention and resources on those areas likely to need attention.

de Little (2002) likens regular monitoring of plantations to a regular medical check up to identify problems as soon as possible to allow early intervention. Management decision can include the intensity and method of monitoring. Monitoring of plantations is a critical part of IPMS. Any automatic spraying in the absence of a monitoring program could raise the following issues:

1. It is wasting resources.
2. It is eliminating natural enemies
3. It is exposing the plantation investment to potentially unnecessary risk (i.e. the risk of an accident).
4. If questioned (from a public relations point of view), there would be little justification for the activity. Aerial application of any product is a very visible operation that draws attention from an increasingly aware public.

Based on the assumed monitoring regime (Appendix 1), monitoring placed increased economic pressure on plantation returns (Figures 7.7 and 7.8). If we consider *E. globulus* management scenario 4, and defoliation scenario 26, the addition of monitoring lowers IRR by 6% (8.4% to 7.9%). It is therefore important that monitoring is as cost effective as possible. Taking de Little's medical analogy (de Little 2002), monitoring should be treated as a package, with a range of issues covered by any inspection. For example, plantation inspection for fire season preparation, nutrient assessment, or weed inspections could include insect pest monitoring.

In order to make a monitoring program more efficient, knowledge of pest insect life cycles is required to ensure correct timing. Monitoring should be through out the full plantation rotation. As shown by Figure 7.6, a single 100% defoliation at age 5 (S39) for *E. globulus* reduces IRR from 10.8% to 5.6% (by 48.1%). If a plantation has had insect attack, it should become a priority for continued surveillance if resources are limited as the impact of subsequent attack can be more significant than a once off attack. Analysis of damage scenarios 46, 47, 48, 49 and 50 for *E. globulus* (Figure 7.6) show that repeated defoliation has a greater impact on MAI and IRR than single defoliation events.

Acknowledgments

The preparation of a desk top study of this nature is always an interesting exercise of bringing together a broad range of information, data, thoughts and concepts. In doing such, the input, wisdom and critique of other is vital. We would like to thank Martin Steinbauer and Saul Cunningham (CSIRO Entomology), Christine Stone (State Forest, NSW) and Nick Collett (Dept of Natural Resources and Environment, Vic) for early, formative discussions about plant response to insect damage. Michael Ryan (USDA Forest Service, Rocky Mountain Research Station) provided stimulating discussion on the source-sink model. The following people are acknowledge for their help in providing data and information: Bill Lawrence (For Mans Pty Ltd), Warren Blyth (Field Air Operations Pty Ltd), John Campbell (Technical Sales Representative, MacSpred Pty Ltd) and John Scott (Executive Officer, Murray Riverina Regional Plantations Committee) for cost information and discussions of the plantation regimes and the operational insect control options proposed. Thanks go to Timbercorp for providing an office space and facilities during MM's visits to WA and to WRF Forestry Pty Ltd for providing access to internal company reports on a number of issues associated with plantation development and harvesting.

8 General discussion and summary

Genetic variation in insect resistance

Insect resistance of *Eucalyptus grandis* and *E. globulus*

The *E. globulus* and *E. grandis* trials incurred similar levels of cumulative damage (mean cumulative damage per tree $\pm$ SD: $172.2\% \pm 63.6\%$ and $208.9\% \pm 60.2\%$ respectively), although the cause of damage varied both between species and between locations of the individual trials. The major cause of damage to the *E. globulus* trials at Lyneham Ridge was Christmas beetles. For the *E. grandis* trials, autumn gum moth was the major pest at Mildura, while brown lace lerp was the major pest at Shepparton. The lack of replication of host tree and major insect pest at different locations limits the ability to draw conclusions from these data. Clearly there is a genotype by environment interaction. The amount of damage a tree is likely to sustain from a given insect species is a function not only of the tree's inherent susceptibility to the insect, but also the interaction between the ecology of the insect, the ecology of the tree and local conditions.

The *E. globulus* trial was established at Lyneham Ridge because this site had a history of autumn gum moth attack and this was the main pest species of interest for this tree species. However, damage by this insect species was low and Christmas beetles were the major pest species. In contrast *E. grandis* is not considered a preferred host of autumn gum moth, yet the Mildura trial suffered sustained high levels of damage caused by this species. Clearly our understanding of the ecology of this pest species and its interaction with different host species was poor and needs to be improved.

Between-provenance variation in insect damage was greater in *E. globulus* than in *E. grandis*. Variation in overall insect damage between *E. globulus* seedlots did not show any clear pattern relating to the geographic location of the seed sources, although some patterns did emerge when damage by individual insect species were examined. Natural provenances of *E. grandis* from the Coffs Harbour region tended to have the least damage, although between-provenance variation in insect damage for the species was generally low. Differences in between provenance variation in insect damage for *E. globulus* and *E. grandis* are discussed in the next two sections.

Between provenance variation in resistance in *Eucalyptus globulus*

There was a three-fold difference in the amount of damage among the 18 provenances of *E. globulus*. Farrow *et al.* (1994) has shown that provenances of *E. globulus* from Tasmania and the Bass Strait Islands were less susceptible to autumn gum moth and leafblister sawfly than mainland provenances. The results from this study show that some provenances from Tasmania and the Bass Strait Islands are also less susceptible to Christmas beetles. No relationship was found between Christmas beetle damage and damage caused by other herbivores. For example, scale insects caused most damage to provenances of *E. g. globulus* from Jeeralang, Lorne, Clarke Island and St Mary's, while two of these provenances (Clarke Island and St Mary's) were among the most resistant to Christmas beetle feeding. However, the level of damage caused by insects other than Christmas beetle was much smaller than the peak Christmas beetle damage. It may have been that the damage levels were below the threshold for differential resistance to insect feeding to be expressed.

When all insect damage was combined, the provenances did not show a geographical pattern of susceptibility to insect attack. The five most resistance provenances and the five least resistant provenances all came from Tasmania, NSW, Victoria and the Bass Strait Islands (see Chapter 4). Farrow *et al.* (1994) suggest that due to its susceptibility to autumn gum moth attack, *E. globulus*

bicostata may not be a suitable plantation species. However, in the current study two provenances of *E. globulus bicostata* (Rylstone and Beechworth) were among the most resistant of the seedlots examined. This result may have been due to the low level of autumn gum moth attack in this study.

Between provenance variation in resistance in *Eucalyptus grandis*

While the insecticide exclusion trials at Shepparton showed that insect damage had a significant impact on the performance of *E. grandis*, no clear pattern of resistance between provenances emerged (Table 8.1). Relative resistance of seedlots varied between trial localities and between plantations within localities. However, variation in resistance among seedlots was low with mean cumulative damage for seedlots at Shepparton ranging from 214% to 263% and from 178% to 213% at Mildura. With such slight variation between seedlots, small changes in damage can result in substantial changes in relative resistance. Other studies of within-species variation in insect damage to eucalypts have shown up to two-fold differences among individuals or provenances (Farrow *et al.* 1994; Floyd *et al.* 1994; Raymond 1995; Stone and Bacon 1994b). Differences of this magnitude are probably required for selection for resistance to be included in breeding programs.

Table 8.1 Summary of the level of resistance to insect attack shown by *E. grandis* seedlots at Mildura and Shepparton

Provenance/seedlot	Shepparton			Mildura		
	Total	Autumn gum moth	Brown lace lerp	Total	A	B
Bellthorpe	6	10	6	8	8	6
Blackdown Tableland ¹	12	2	12	15	15	15
Boambee	1	5	2	-	-	-
Bruxner Park	11	7	9	5	4	5
Bulahdelah	2	3	5	13	13	9
Coffs Harbour Seed Orchard	10	9	11	9	3	11
Lake Cathie	8	12	1	2	1	2
Langleys Road	9	4	10	7	9	4
Loxton selects	-	-	-	1	2	1
Mt George	-	-	-	11	11	8
Orara SF	-	-	-	14	14	14
Pine Creek	4	8	3	6	5	10
Pretoria	-	-	-	3	6	3
Wahau Trig	5	11	4	10	10	12
Wedding Bells	7	6	8	4	7	7
Woondum	3	1	7	12	12	13

Note: Ranks are based on based on cumulative damage levels and range from 1 (least damage) to 15 (most damage). For both sites, the total rank is for all damage by all insect species. At Shepparton ranks for the two major insect species are also given. At Mildura there was only one major pest species and ranks are given for the two modules.

¹ *E. saligna*

Environmental factors, both abiotic and biotic, may influence the magnitude and expression of resistance (Panda and Khush 1995). Seedlots of *E. grandis* planted at Deniliquin as a reference for the performance of *E. benthamii* and *E. dunnii* showed much greater variation in damage levels (~2.5 fold) than seen at Mildura and Shepparton. Conditions at Mildura and Shepparton may have suppressed the expression of resistance or reduced its magnitude in comparison to Deniliquin. Dehydration stress is known to reduce plant resistance to insect attack (Panda and Khush 1995) with the effects persisting for some time after rehydration (Haglund 1980). As discussed in Chapter 2, in Mediterranean climatic conditions such as at Mildura, *E. grandis* can suffer from dehydration stress even when soil water is available. Dehydration stress occurred at both Mildura and Shepparton due to

inadequate supply of irrigation water and the location of the Mildura-A plantation on the side of a ridge with high exposure to hot summer winds. In contrast, trees with the best growth rate at Deniliquin performed well (see Chapter 3), indicating that water stress was unlikely to have been a limiting factor.

No data are available to determine if dehydration stress is a contributing factor to the poor performance of *E. grandis* at Mildura and Shepparton, let alone whether it reduces insect resistance. Certainly the growth rates of the Mildura and Shepparton trials were quite poor (see Chapter 2). *Eucalyptus grandis* has been reported to grow well at Loxton (Arnold *et al.* 1996), which has a similar climate to Mildura, demonstrating that this species can be grown successfully in this type of climate. Given the doubts over the performance of *E. grandis* in these trials it may be too early to exclude the species from further research on insect resistance. However, future trials must achieve growth rates comparable to those reported for Loxton (Arnold *et al.* 1996) and Wagga Wagga (Myers 1994) for conclusions about levels of insect resistance to be useful.

Insect resistance of *Eucalyptus benthamii*, *E. dunnii* and *Corymbia maculata*

In the Deniliquin species and provenance trials, *C. maculata* was least attacked by insects, *E. benthamii* was most attacked and *E. dunnii* attack was intermediate (Table 8.2). *Eucalyptus benthamii* seed orchards consisted of *E. benthamii*, and the closely related *E. kartzoffiana* and *E. dorrigoensis* with the latter being more susceptible to attack by autumn gum moth (Table 8.1). The relative level of damage between the species did vary with changes in the level of overall attack. For example in 1999 when the populations of autumn gum moth were highest, mean damage at Barclay was 48%, 47% and 28.3% for *E. kartzoffiana*, *E. dorrigoensis* and *E. benthamii* respectively.

Variation in damage levels among *E. dunnii* seedlots was much less than for *E. benthamii*. The main insect herbivores of *E. benthamii* were autumn gum moth and leafblister sawfly and there was no evidence of cross-resistance. In fact, seedlots with greater resistance to autumn gum moth tended to have less resistance to leafblister sawfly and *visa versa*.

Table 8.2 Mean annual damage (Mean $\pm$ stdev (range)) for each species used in this study. Values for Shepparton and Lyneham Ridge are for unsprayed plants only.

Site	Species	Mean annual damage (%)	
Lyneham	<i>E. globulus</i>	20.0 $\pm$ 16.4	(0–75)
Shepparton	<i>E. grandis</i>	28.8 $\pm$ 19.3	(0–100)
Mildura-A	<i>E. grandis</i>	26.3 $\pm$ 11.7	(0–100)
Mildura-B	<i>E. grandis</i>	24.5 $\pm$ 9.3	(0–49)
Barclay	<i>E. benthamii</i>	27.8 $\pm$ 15.6	(0–100)
	<i>E. dorrigoensis</i>	31.1 $\pm$ 17.9	(0–78)
	<i>E. kartzoffiana</i>	47.8 $\pm$ 15.7	(0–100)
	<i>E. dunnii</i>	23.6 $\pm$ 14.2	(0–95)
	<i>C. maculata</i>	0.8 $\pm$ 3.2	(0–35)
	<i>C. henryi</i>	1.0 $\pm$ 1.9	(0–10)
Crossley	<i>E. benthamii</i>	22.0 $\pm$ 14.8	(0–90)
	<i>E. dorrigoensis</i>	20.5 $\pm$ 13.8	(0–58)
	<i>E. kartzoffiana</i>	48.8 $\pm$ 22.0	(0–90)
	<i>E. dunnii</i>	18.5 $\pm$ 12.6	(0–95)
	<i>C. maculata</i>	2.1 $\pm$ 5.1	(0–70)
	<i>C. henryi</i>	2.1 $\pm$ 2.6	(0–15)

On the basis of the trials at Deniliquin, there appears to be insufficient variation in resistance in *E. dunnii* seedlots to warrant further work on the development of resistant seedlots. In contrast *E. benthamii* appears to offer more promise as a candidate for genetic improvement. However, it should also be noted that, while *E. dunnii* showed little variation in insect resistance as a species, it was generally more resistant to insect attack than *E. benthamii* seedlots. For example the most resistant *E. benthamii* seedlots incurred similar levels of damage to the mean of all *E. dunnii* seedlots.

Impact assessment

RGR vs volume

The degree of damage to a plant is a function of pest intensity, the types of feeding behaviour of the pest species and plant resistance characteristics. A variety of approaches can be used to evaluate plant resistance to pest damage. In commercial situations where the ultimate aim of host plant resistance is to minimise reductions to plant yield, resistance is usually measured in terms of yield loss to parts of the plant of economic value (Panda and Khush 1995). In forestry the whole plant is generally of commercial value and assessments of impacts concentrate on alterations to growth rates or to the final size of plants. As well as impeding growth, insect damage can also alter how a plant grows. The obvious example of this is impacts on plant form due to damage to the growing tip. The tree may continue to grow at the same rate after the damage and produce the same amount of wood, but the useable timber may be greatly reduced due to the way the plant responds to damage.

One of the most obvious forms of insect damage that has a direct impact on the growth of the plant through a reduction in leaf area and photosynthetic rate is defoliation. The impact of defoliation also depends on the leaf area index (LAI) of the plant such that plants with a low LAI are more seriously affected by defoliation. When the LAI is high, self-shading of leaves occurs and mild levels of defoliation may actually increase the rate of carbon fixing by decreasing self-shading. The impact of a given level of defoliation depends also on the age of the leaves removed and the distribution of damage, both within and between leaves and in space and time (Crawley 1997).

During this study we used tree volume as the measure of plant yield. We also used a derived index, relative growth rate (RGR), as a measure of the rate of plant growth. Both plant volume and RGR were used to detect plant resistance to insect damage.

Plant volume provides the most direct estimate of the potential economic impact of insect damage on the plant. The RGR measures the rate of change over a set period and provides a way to measure the impact of damage over different time frames and to look at how plants respond to various conditions. For example, after major damage by Christmas beetles the relative growth rate of sprayed *E. globulus* plants was greater than that of unsprayed plants whereas before spraying the opposite was true (see Chapter 4). Also, because the plant volume at the start of the period of interest is included in the calculation, the RGR provides a useful way to compare impacts on different sized trees. This was the case at Mildura where the mean volume of trees in the sprayed monitoring modules was greater than those in the unsprayed modules before spraying started. This raised problems in determining the subsequent impact of autumn gum moth damage on the unsprayed trees. If volume was used to assess impact, it would be difficult to determine if differences between sprayed and unsprayed tree were due to the insects or the initial differences. By analysing growth rate it was possible to show that autumn gum moth feeding did impact on the plants, but only after two years of heavy defoliation.

Resistance vs growth rate

Plants show considerable variation in growth and susceptibility to herbivores both within and between genotypes (Bryant *et al.* 1983; Coley *et al.* 1985; Denno and McClure 1983; Herms and Mattson 1992) and it has been hypothesised that variation in susceptibility to herbivores is largely determined by variation in amounts and types of plant secondary metabolites (Fraenkel 1959). Moreover, it is widely accepted that there is a trade-off between plant growth and chemical defence because these functions compete for limiting resources (Bazzaz *et al.* 1987; Chapin *et al.* 1990). Thus, fast growing plants (species, populations, or individuals) are hypothesised to be more susceptible to herbivores than slow growing plants (species, populations, and individuals).

Trade-offs between defence and growth potentially pose an important practical problem in agriculture and forestry, where fast growing genotypes with high yield have been artificially selected and where growth and yield are enhanced by irrigation and fertiliser applications. Moreover, the level of spatial variation in plant chemical defence in crop fields and plantations is typically much less than that in natural environments (Denno and McClure 1983). Once pest species establish themselves, they can spread quickly and cause considerable damage to crops or plantation trees. To compensate for the reduced level of natural resistance to insect attack, insecticides are used to control pests in fields and plantations. However, periodic large-scale preventative spraying is costly both to farmers and plantation owners and to the general public through the hidden cost of environmental damage. It also raises the spectra of pest species developing resistance.

Examples of these types of trade-offs can be found in this study. *Corymbia maculata* is known to be highly resistant to insect attack and during this study it clearly had the lowest damage levels of any species. However, increased resistance was traded off against slow growth. The fastest growing seedlots of *C. maculata* grew at about half the rate of the fastest growing seedlots of *E. benthamii* and *E. dunnii* at the same sites.

Trade-offs also occur at the provenance and family level within species. The genetically improved seedlot, Coffs Harbour Seed Orchard, was one of the fastest growing *E. grandis* seedlots. However, it also was one of the most susceptible to insect attack.

Given that there are trade-offs between growth and resistance, the obvious question is on what criteria should material be chosen for planting. Faster growing trees may produce more timber in a shorter time, and their superior growth rates may help them grow through low to moderate levels of insect attack. However, at higher levels of attack, they may suffer growth-stunting insect damage if insecticides are not used. The cost of insect control must then be balanced against the returns from higher growth rates. Slow growing resistant trees will not have the same insect control cost, but the time between planting and harvest may be uneconomical.

Acute vs chronic

Not all insect damage has the same effect on plant growth. The timing, intensity and frequency of damage as well as the part of the plant attacked can influence the impact of herbivory on a plant. Different species feeding on the same plant also have the potential to influence each other, either by modifying the host plant or by competing for resources (Crawley 1997).

Several different species of insect regularly attacked plants of *E. globulus* at Lyneham Ridge. The damage caused to the trees can be separated into two types: acute damage was caused by insects such as scale insects (*Eriococcus* spp., Hemiptera: Eriococcidae) and autumn gum moth (*Mnesampela privata*, Geometridae, Lepidoptera) with trees suffering small amounts of damage throughout the trial, and chronic damage occurred when Christmas beetles (*Anoplognathus* spp., Coleoptera: Scarabaeidae) caused intense annual defoliation events. Christmas beetles typically feed in large groups, and a group

of beetles may spend from a few days to a few weeks feeding in a patch of trees (e.g., plantations). In contrast, episodes of acute damage occurred over much longer time period (3 months or longer).

Eucalypts show a range of responses to varying levels of defoliation. Carne *et al.* (1974) suggested that vigorously growing young *E. grandis* were unlikely to have their subsequent growth impacted by defoliation below about 50%. In contrast, light defoliation of *E. delegatensis* R.Baker by the phasmatid, *Didymuroa violescens*, caused a significant reduction in diameter growth during two successive seasons (Mazanec 1968).

The data from Lyneham Ridge on *E. globulus* suggest that insect damage affects plant growth more strongly in populations when the potential growth rates are intermediate rather than being very high or very low. Of the two types of damage, very severe or repeated, severe acute damage was predicted to have stronger negative effects on plant growth than mild chronic damage repeated over the life time of a plant. However, not all the types of insect damage occurred during the study (e.g., severe chronic damage), and further work is needed to understand how chronic and acute damage interacts with plant growth.

Summary of actual impacts

Insect exclusion experiments with Eucalyptus grandis and E. globulus

The results of the insect exclusion experiments on *E. grandis* and *E. globulus* showed that insect damage impacted on growth of the two species. Autumn gum moth and brown lace lerp damage to *E. grandis* over 6 years caused a loss in volume of 11%. Feeding over a five-year period by a number of insect species including Christmas beetles, autumn gum moth and scale insects caused an 18% reduction in volume of *E. globulus* trees. These losses are substantially less than reported for other insect-eucalypt combinations. For example in an insecticide exclusion experiment with two year old *E. regnans* trees, defoliation by *Chrysophtharta bimaculata* (Olivier) (Coleoptera: Chrysomelidae) in their first year of growth resulted in a 45.6% and 52.1% loss of height and basal area increment respectively (Elliott *et al.* 1993).

The amount of growth suppression from insect attack varied significantly among provenances. The unsprayed *E. grandis* provenances showed a 7%–41% reduction in volume compared to the sprayed provenances. For *E. globulus* provenances, growth suppression in volume ranged from 0.5% to 56%. The impact of damage tended to be greatest on the fastest growing provenances. For example Coffs Harbour Seed Orchard, Bulahdelah and Lake Cathie were, by volume, the largest *E. grandis* provenances in the sprayed treatment at Shepparton. Insect damage caused reductions in volume of 35%, 31% and 38% respectively.

By examining the interaction between damage and growth it is possible to predict how well plants will grow under different levels of insect attack. It was found that although the faster growing provenances tended to suffer greater damage, their overall performance was still very good. This appears to be because their superior growth rates compensates for the increased damage. For *E. grandis* and *E. globulus* it was found that Coffs Harbour Seed Orchard and Geeveston respectively, were the best performing provenances for each species even though they suffered some of the highest damage. However, in the remaining *E. globulus* provenances, the level of insect attack was critical in determining their overall performance. At low levels of attack, faster growing provenances from Traralgon, Flinders Island and St Mary's ranked well. However, at higher levels of damage they are predicted to grow less well and slower growing provenances from King Island, Cape Barren Island and Black Range are predicted to do better. For *E. grandis*, the Coffs Harbour Seed Orchard provenance was the only fast growing seedlot predicted to perform well over a range of damage levels. Seedlots with intermediate growth and damage rates such as Bruxner Park and Pine Creek, were predicted to do better in terms of growth than seedlots with greater growth potential but low levels of insect resistance.

It should be remembered that the data these predictions are based on was limited. Insect exclusion trials were only conducted at a single site for each species and the amount of damage received by *E. globulus* and *E. grandis* during this study was not high. If plants do not respond linearly to damage, then the predicted response of provenances to high levels of damage (>70%) should be treated with some caution. This is illustrated by the performance of the *E. grandis* provenance Coffs Harbour Seed Orchard at Mildura. Based on the data from Shepparton and taking into account both growth and insect resistance this seedlot was predicted to have good growth at most probabilities of insect attack (see Chapter 2). At Mildura, prior to 1998, it was considered one of the best performing seedlots (see Appendix 3), but after two years of heavy defoliation by autumn gum moth it ranked behind improved seedlots from Pretoria and Loxton, and the Bruxner Park provenance. Pine Creek, another *E. grandis* provenance predicted to do well based on the Shepparton data, had a mixed result at Mildura. It ranked as one of the slowest growing seedlots at Mildura-A, while at Mildura-B, ranked in the top five fastest growing seedlots.

***Eucalyptus benthamii* and *E. dunnii* seed orchards at Deniliquin**

This study found little evidence of insect damage impacting on the growth of provenances in the *E. benthamii* and *E. dunnii* seed orchards. Large within site variation added considerable noise to the data while the overall cumulative levels of damage were about half that received by plants at the other sites in the study. With no insect exclusion treatments it was difficult teasing out insect damage effects from other factors such as within site spatial variation and inherent variation in growth rates.

With so much variation it was not surprising that there was a two to seven fold difference in the mean plant volume of seedlots between the different sites and species and that few seedlots performed consistently across the sites. Overall the *E. dunnii* and *E. benthamii* seed orchards had similar growth rates to the *E. grandis* reference seedlots included in the seed orchards (Table 8.3). However, the best performing trees did considerably better than the reference seedlots. Growth was the most consistent at the Barclay seed orchards and *E. dunnii*, *E. benthamii* and *E. kartzoffiana* averaged growth rates of $16.7 \text{ dm}^3 \text{ y}^{-1}$, $13.4 \text{ dm}^3 \text{ y}^{-1}$ and $10.4 \text{ dm}^3 \text{ y}^{-1}$ respectively at this site. In comparison the growth rate of the *E. grandis* reference seedlots was $4.7 \text{ dm}^3 \text{ y}^{-1}$ in the *E. benthamii* seed orchard (Coffs Harbour SSO i) and $16.1 \text{ dm}^3 \text{ y}^{-1}$ in the *E. dunnii* seed orchard (Coffs Harbour SSO ii). Growth of *E. dorrigoensis* was considerable less than the other species at $6.9 \text{ dm}^3 \text{ y}^{-1}$.

Overall there was a three-fold difference in mean volume between *E. dorrigoensis* and the other provenances in the *E. benthamii* seed orchard, although this difference decreased to 1.5 fold when *E. dorrigoensis* was excluded and to 1.4 fold when only the *E. benthamii* provenances were included. Among the *E. dunnii* provenances there was a 1.5 fold difference in mean volume. Trees from the Nepean River region had the best growth across all sites of all the *E. benthamii* provenances. Among the *E. dunnii* provenances no one seedlot stood out with trees from the Acacia Creek, Haystack and Koreelah SF provenances consistently achieving good growth.

Observations of insect–tree interactions

New observations

Due to its preference for the juvenile foliage of blue gum eucalypts, autumn gum moth has been thought of as a pest of young plants of species from that group of eucalypts. However, observations presented in this study show that it can equally be a pest of mature plants and of other species such as *E. grandis*, usually thought not to be at risk.

Soft juvenile or young foliage is essential for the development of early instars. However, as larvae develop the types of leaves they can feed on change. As preferred leaves are consumed, feeding can move onto older juvenile foliage on the inner branches or more mature leaves higher in the canopy.

Late instar larvae may also move to non-preferred or non-host species if faced with a shortage of preferred foliage. As the majority of material consumed by larvae is by later instars, high survival rates of early instars can lead to large populations of late instar larvae that can completely defoliate trees, even when a high proportion of the leaves are mature.

These observations suggest that in its endemic range the types of leaves the first instar larvae can feed on determine the host plant range of autumn gum moth. Later instars can potentially feed on a much broader range of foliage types and plants, but ecological constraints limit the opportunities for this to occur.

Table 8.3 Mean annual height increments (Mean $\pm$ stdev (range)) for each species used in this study

Site	Species	Height class	Height growth increment (m year ⁻¹)	
Lyneham	<i>E. globulus</i>	-	1.60 $\pm$ 0.37	(0.38–2.50)
Shepparton	<i>E. grandis</i>	-	1.97 $\pm$ 0.35	(0.20–2.65)
Mildura-A	<i>E. grandis</i>	-	1.39 $\pm$ 0.31	(0.50–2.39)
Mildura-B	<i>E. grandis</i>	-	1.50 $\pm$ 0.38	(0.43–2.49)
Barclay	<i>E. benthamii</i>	1	1.51 $\pm$ 0.39	(0.45–2.98)
		2	2.88 $\pm$ 0.48	(2.17–4.23)
	<i>E. dorrigensis</i>	1	1.53 $\pm$ 0.42	(0.57–2.76)
		2	2.48 $\pm$ 0.26	(2.18–2.97)
	<i>E. kartzoffiana</i>	1	1.41 $\pm$ 0.40	(0.52–2.31)
		2	2.86 $\pm$ 0.34	(2.24–3.73)
	<i>E. grandis</i> reference seedlot	1	1.53 $\pm$ 0.28	(1.06–1.88)
		2	2.27 $\pm$ 0.03	(2.23–2.30)
	<i>E. dunnii</i>	1	1.80 $\pm$ 0.34	(0.20–1.80)
		2	2.65 $\pm$ 0.47	(1.83–3.77)
	<i>E. grandis</i> reference seedlot	1	1.01 $\pm$ 0.36	(0.60–1.43)
		2	2.98 $\pm$ 0.29	(2.33–3.43)
	<i>C. maculata</i>	-	1.83 $\pm$ 0.66	(0.37–3.58)
	<i>C. henryi</i>	-	1.96 $\pm$ 0.58	(0.42–3.40)
Crossley	<i>E. benthamii</i>	1	0.66 $\pm$ 0.15	(0.15–0.87)
		2	0.93 $\pm$ 0.22	(0.25–1.69)
	<i>E. dorrigensis</i>	1	1.60 $\pm$ 0.28	(1.17–2.75)
		2	0.92 $\pm$ 0.28	(0.20–1.71)
	<i>E. kartzoffiana</i>	1	1.51 $\pm$ 0.29	(1.17–2.18)
		2	0.85 $\pm$ 0.17	(0.47–1.16)
	<i>E. grandis</i> reference seedlot		0.92 $\pm$ 0.14	(0.75–1.09)
			1.71 $\pm$ 0.40	(1.22–2.68)
	<i>E. dunnii</i>	1	1.51 $\pm$ 0.28	(1.17–2.14)
		2	2.57 $\pm$ 0.42	(1.80–3.80)
	<i>E. grandis</i> reference seedlot		1.26 $\pm$ 0.34	(0.77–1.73)
			2.40 $\pm$ 0.31	(1.90–2.93)
	<i>C. maculata</i>	-	1.24 $\pm$ 7.40	(0.10–2.26)
	<i>C. henryi</i>	-	1.38 $\pm$ 0.35	(0.47–2.08)

Note: Means from the Deniliquin sites were calculated for the period before culling began (1995 to 1998). Values for Shepparton and Lyneham are for unsprayed plants only. For an explanation of the height classes at the Deniliquin sites, see Chapter 3.

In planted stands of eucalypts, the ecological constraints that limit the chances of late instar larvae feeding on non-host species or non-preferred foliage appear to be either relaxed or removed. The critical difference is likely to be the greater availability of either juvenile or young foliage suitable for development of the early instars of the moth. In natural stands, females are likely to have to search extensively for foliage suitable for oviposition, with immature leaves likely to be rare and dispersed among predominantly mature foliage. Furthermore, suitable leaves are likely to have already been utilised by another autumn gum moth or other insect. Limited availability of suitable leaves restricts population development and small populations are less likely to 'break out' onto non-preferred foliage or hosts.

In contrast to natural forest, plantations generally have proportionally more juvenile foliage, even when trees have changed to adult foliage as the outbreaks at Mildura and Loxton demonstrated. In addition, suitable foliage tends to be more concentrated in a plantation. The high density of trees results in rapid canopy closure and shading of lower branches. Shaded leaves are inclined to have a thinner epidermis and cuticle (Niinemets and Kull 1994; Simon *et al.* 1973). This may alter their susceptibility to autumn gum moth and female moths at Mildura showed a preference for shaded leaves. Shaded branches also tend to stay in juvenile foliage longer than normal. Plantations can have large edges, an artefact of their size and isolation. Trees at the edge of a stand can have different growth forms to trees within a stand. At Loxton many of the plants on the edge of the stands had failed to self prune and carried a relative large amount of soft foliage suitable for autumn gum moth oviposition.

Generally the susceptibility of older plantations to attack by autumn gum moth can be reduced by silvicultural treatments. Once trees are predominantly carrying adult foliage or canopy closure has occurred, pruning of shaded branches and lower branches at the edge of stands will reduce the risk of outbreak. This removes the bulk of foliage suitable for autumn gum moth oviposition and development of early instars.

Tree size

Herbivores rarely kill their host plants, instead they act more like parasites than predators of plants (Crawley 1997). Exceptions include outbreaks of some Lepidoptera that can kill trees after repeated defoliation over several years. In this study, autumn gum moth was found to increase the rate of mortality of trees at Mildura, although the impact was limited to the smallest trees. In general the trees that died were those that normally would be culled from a plantation. They were small, and because of competition for light by the larger plants were unlikely to grow much larger. Their loss was of no economic significance.

Stress vs damage (Mildura dry stress)

Under conditions of low humidity, dry stress appears to retard the growth of *E. grandis*. This can occur even when irrigation levels are high and there is adequate soil water (Myers *et al.* 1996). Low daytime humidity was common over much of the growing season at Mildura which, combined with interruptions to the supply of irrigation water, probably retarded growth of the *E. grandis* at Mildura. This may be why *E. grandis* growth rates were less than expected (Chapter 2, Appendix 3).

Reduction in growth by dry stress may interact with insect resistance. Plant stress had been hypothesised to make plants more susceptible to insect attack (White 1993), although the hypothesis is not without controversy (Larsson 1989). Some of the controversy arises because it can be hard to define just what stress is. There are many different kinds of stress, many idiosyncratic responses of plants and equally diverse responses by insect herbivores (Speight *et al.* 1999). Insects vary in the way they respond to plant stress caused by water deficit. A study of the responses of eight species of leaf-gallers to dry stress of their host plant, creosote bush (*Larrea tridentata* [DC.] Cov.), found that five

species had a greater abundance on stressed plants, two species had a greater abundance on unstressed plants and one species showed no preference (Waring and Price 1990). Miles *et al.* (1982) found no influence of dry stress on the performance or survival of leaf beetles on young *Eucalyptus camaldulensis*, even though stress did alter the nutritional quality of the leaves. Stone and Bacon (1994b) found a significant correlation between water stress and herbivory in natural stands of *E. camaldulensis*, although these differences appeared to be related to changes in leaf morphology, rather than leaf chemistry. It is also generally thought that mild plant stress may favour sap-sucking insects but disadvantage other feeding guilds such as chewing insects (Larsson 1989).

The response of autumn gum moth to dry stress in its host plants is unknown. Two years of autumn gum moth damage caused a significant decrease in the relative growth rate of plants from the Loxton seedlot planted at Mildura (see Chapter 2). This implies that autumn gum moth feeding was suppressing tree growth beyond the impact of dry stress. However, since there are no data on the magnitude of any reduction in growth caused by dry stress, it is impossible to determine whether there was any interaction between insect damage and dry stress.

Management

Genetic selection

Growth rates of *E. grandis* in these trials were poor, presumably as a result of dry stress. This emphasises the importance of adequate irrigation when this species is grown in Mediterranean climates. Conclusions about the impact of damage on this species are potentially ambiguous due to possible interactions between insect damage and dry stress. Between provenance variation in damage was low, suggesting that there is little potential for a tree improvement program for enhanced resistance. However, two reference seedlots of *E. grandis* planted as part of the species trials at Deniliquin showed much greater variation in both growth and damage levels. Further work on evaluating insect resistance of seedlots of this species will be needed before any satisfactory conclusions can be made. Research to identify seedlots with the greatest tolerance of low humidity may be useful.

Eucalyptus globulus is one of the fastest growing eucalypt species on irrigated or higher rainfall sites (>700 mm annual rainfall) (Stone *et al.* 1998). The mean annual rainfall in the region of the *E. globulus* trial at Lyneham Ridge is about 600 mm which is suboptimal but within the range of 600–1500 mm required for growth of the species (Abbott and Wills 1996). Consequently, growth rates at Lyneham Ridge were poor. In trials in southern Australia, including the southern Murray-Darling Basin, no single provenance of *E. globulus* has shown consistent superiority (Elliott *et al.* 1998). In trials reported here, the provenance from Geeveston showed resistance to insects and fast mean growth. However, fast growing individuals and provenances generally tend to be more susceptible to insect attack. Therefore, selecting the fastest growing trees may not maximise returns if insect attack occurs. Unfortunately, insect outbreaks are often unpredictable in space and time. The risk of losses from insect attack could be managed by planting a mix of provenances including less resistant but fast growing seedlots (Geeveston, St. Mary's, Traralgon, and Flinders Island) and more resistant but slower growing seedlots (King Island, Black Range, and Cape Barren Island) (Raymond 1995). The next step in selection of herbivore resistant *E. globulus* will be to examine the heritability of plant growth and resistance to herbivores.

The extremely variable growth rates of *E. dunnii* and *E. benthamii* at Deniliquin confounded attempts to explore the impact of insect damage on plant performance. Both species are capable of very high growth rates (Elliott *et al.* 1998; Myers 1994) as was evident by individuals at Deniliquin that were not retarded by adverse site effects. Differences in growth and insect damage among *E. dunnii* provenances were small indicating that provenance selection in this species is likely to provide only minor gains in growth rates and insect resistance. Variation in growth and insect damage among

provenances of *E. benthamii* was greater and provenance selection in this species is likely to be profitable. The next step in selection of herbivore resistant *E. benthamii* will be an insect exclusion trial using a subset of seedlots based on a carefully interpretation of the Deniliquin trial results.

Silvicultural interactions

The outbreak of autumn gum moth at Mildura and Loxton highlighted the importance of silvicultural practices in controlling insect pests. To reduce the risk of developing outbreak populations of autumn gum moth, removal of small, poorly growing or self-sown understory trees along with the pruning of lower branches with juvenile or shaded foliage should be a regular part of plantation maintenance. In *E. grandis* plantations, this material provides a source of leaves on which early instar autumn gum moth larvae can develop.

Removal of small trees and shaded lower branches has two benefits. Firstly, the abundance of late instar larvae may be reduced by reducing the amount of preferred foliage for autumn gum moth oviposition and early instar development. This will reduce defoliation damage as well as limit the size of the population in following years. Secondly, removal of the lower branches makes it easier to get machinery into a plantation and this is important if ground-based insecticide spraying is required. For insects like autumn gum moth that aggregate on the lower branches as young larvae, aerial spraying can be ineffective. Spray penetration may be restricted and mortality rates may be low when the canopy is dense. The most effective means of applying insecticide against such insects is often by ground-based spraying which requires access between rows. Spray penetration is also increased by removal of lower branches.

Chemical control

Over the last three decades, increasing problems with the development of insect resistance and concerns about adverse environmental impacts has lead to the search for alternatives to synthetic insecticides. Two promising approaches that have come from this research are the use of pathogens such as bacteria and virus as bioinsecticides and the development of insecticides that mimic and disrupt the action of insect growth hormones. Bioinsecticides will be discussed later in this section.

Hormones control the growth and development of insects. Juvenile hormones are involved with the control of larval development and pupation. Moulting hormones (ecdysones) control skin shedding in nymphs and larvae (Speight *et al.* 1999). Synthetic analogues of these compounds are now available as insecticides and disrupt normal growth and development. They also tend to have a much narrower host spectrum than conventional insecticides and have low acute toxicity to mammals, birds and fish (Farrow 1996).

The mode of action of these insecticides depends on whether they are based on juvenile or moulting hormones. Juvenile hormone analogues often do not kill insect but instead induce morphological deformities. Larvae may be unable to complete development, forever moulting to another larval instar until death (supernumerary larvae) or development may become stuck in intermediate stages such as larval-pupal or larval-adult intermediates. Adult stages may be affected through sterility, reduced egg production or inhibited oviposition (Farrow 1996). Insecticides based on juvenile hormone analogues tend to be more useful against insects where the adult stage is the pest or disruption of reproduction is needed. Ecdysone based insecticides tend to be more immediately toxic, inducing lethal moults in target species. Lepidopteran larvae generally cease feeding within 4–16 hours of ingesting these insecticides and by 24 hours the lethal moult has begun (Farrow 1996). In this way the ecdysone analogues act more like traditional insecticides.

Trial spraying of MIMIC™, an ecdysone insecticide with tebufenozide as the active ingredient, was carried out at Mildura against autumn gum moth on *E. grandis* in 1998 and 1999. MIMIC™ is not

registered in Victoria for use against autumn gum moth and spraying was undertaken as “legal off-label use” for the purposes of research.

A single application of MIMIC™ 700 WP at a rate of 258 g ha⁻¹ was made in May 1998. This is twice the registered label rate for the use against lepidopteran larvae. The adhesive Bond was added at the label rate and the insecticide solution was applied using an orchard air-blaster. MIMIC™ caused mortality to all autumn gum moth larval instars. By the end of the autumn gum moth feeding season in July defoliation of sprayed trees was 9.5%±16.7% (0%–100%) and of unsprayed trees was 93.5%±12.8% (50%–100%). Defoliation of sprayed trees was below the control threshold of 15–20%. In 1999, autumn gum moth again threaten to cause significant defoliation and a single application of MIMIC™ 700 WP at the registered label rate of 172 g ha⁻¹ was made in May 1999. BS 2000 was used as the adhesive at the label rate. Autumn gum moth density was lower than in 1998 and the level of protection against subsequent defoliation was much better. Defoliation of sprayed trees by the end of the autumn gum moth feeding season was 1.34%±11.5% (0%–100%) and of unsprayed trees was 64.7%±34.0% (0%–100%).

MIMIC™ appears to be a promising insecticide for the control of autumn gum moth although more research is needed on the efficacy of the insecticide. Larval mortality rates and lethal dosages for the different instars need to be quantified so that more efficient application rates can be developed. While MIMIC™ appears non-toxic to a wide variety of non-lepidopteran insects (Farrow 1996), its impacts on non-target forest Lepidoptera is unknown.

The Centre for Forest Tree Technology in the Department of Natural Resources and Environment of Victoria has trialed various insecticide against several species of insect pests of eucalypts (Neumann 1996; Neumann and Collett 1997a; Neumann and Collett 1997b). Trials were carried out in north-central Victoria and insecticides tested were carbaryl, chlorpyrifos, fenthion, malathion, pyrethrins and the systemic insecticides dimethoate and omethoate. The bioinsecticide dipel (*Bacillus thuringiensis*) was also tested but only against autumn gum moth. All insecticides were tested at the manufacturers recommended concentration and at half and twice those concentrations. The target pest species were autumn gum moth on *E. globulus*, leafblister sawfly on *E. grandis* and steelblue sawfly (*Perga affinis affinis* Kirby, Hymenoptera: Pergidae) on eight species of eucalypts (*E. camaldulensis*, *E. cladocalyx* F.Muell., *E. desmondensis* Maiden & Blakely, *E. globulus*, *E. grandis*, *E. occidentalis* Endl., *E. pryoriana* L. Johnson, and *E. saligna* Smith). All host plants were at irrigated sites.

Against all three pest species aqueous suspensions of malathion at the manufacturers recommended concentration caused high mortality rates. Solutions of 0.01% malathion caused 100.0% mortality of early instar autumn gum moth larvae and 95.9% mortality of steelblue sawfly larvae within two days of application (Neumann and Collett 1997a; Neumann and Collett 1997b). A 0.12% solution of malathion caused 81.8% mortality of larvae and 67.1% mortality of prepupae, pupae and pharate adults of leafblister sawfly (Neumann 1996). Slightly higher mortalities were achieved against leafblister sawfly using the highest concentration of malathion (0.24%) and carbaryl (0.20%). Larval mortalities were 90.4% and 89.5% and prepupae, pupae and pharate adult mortalities were 76.3% and 84.2% respectively. The pyrethrins, chlorpyrifos and fenthion also caused high mortality to some of the pest species. A 0.02% solution of fenthion and a 0.01% solution of the pyrethrins caused 100% and 90.7% mortality respectively, against steelblue sawfly. Pyrethrins (0.01%) and chlorpyrifos (0.25%) caused 94.7% and 96.8% mortality respectively against autumn gum moth larvae. While fenthion is cheaper to spray than malathion or pyrethrin, malathion has a low human health hazard rating and the pyrethrins appear to be the least stable of the three insecticides in the environment (Neumann and Collett 1997b). Chlorpyrifos has a higher mammalian toxicity and slower rates of degradation than malathion or the pyrethrins (Neumann and Collett 1997a). Malathion was considered the best option of all the insecticides tested after taking account of operational, environmental and safety factors (Neumann 1996; Neumann and Collett 1997a; Neumann and Collett 1997b). It produced high efficacy at moderate application rates, has low mammalian toxicity and relatively low environmental impact.

This research provides a good basis for continued development of insecticide control options for pests of plantation trees. Mortality from natural enemies was low (3.6% for autumn gum moth and 7.0% for leafblister sawfly) or absent (steelblue sawfly) at all three trial sites. Research is needed on the possible negative impacts of these insecticides when there is considerable pest mortality by natural enemies. While malathion was generally the best option, reliance on one insecticide raises the risk of the development of insecticide resistance. Future research is needed to expand the choice of chemical control options. For example the effectiveness of fenthion and carbaryl is likely to be enhanced at higher concentrations and work is needed to quantify the best application rates for these insecticides. In addition, not all of the insecticide-pest species combinations tested are registered for use in plantations and spraying was undertaken as “legal off-label use” for the purposes of research. Formal registration of some of these products needs to be established.

Among the insecticides tested by Neuman and Collett was the bioinsecticide dipel. Bioinsecticides tend to have greater specificity than synthetic insecticides and often are non-toxic to vertebrates. Thus, they are better suited for use in IPM strategies where the impact of insecticides on beneficial insects is important. The entomopathogenic bacteria, *Bacillus thuringiensis* has been used as bioinsecticides for over 30 years (Silva-Filha and Regis 1997) and is the active ingredient of dipel. The toxicity of *B. thuringiensis* is caused by the action of proteins called δ -endotoxins, or insecticidal crystal proteins, which are activated by insect gut proteases. The toxin then binds to specific receptors of the brush border membrane of the hindgut epithelial cells, creating pores that cause cells to swell and lyse (Tabashnik 1994). The toxin is specific to insects and δ -endotoxins from different *B. thuringiensis* strains are often highly specific to different groups of insects.

Neumann and Collett (1997a) reported that dipel did not achieve the same high efficacy against autumn gum moth as did malathion, the pyrethrins and chlorpyrifos. However, it is possible that if mortality was assessed more than two days after application, higher mortality may have been observed. *Bacillus thuringiensis* var. *kurstaki* (Foray 48B) was also found to be effective against autumn gum moth in Tasmania (H. Elliott and R. Bashford pers. comm. in Neuman and Collett (1997)) More work is needed on identifying the strains of *B. thuringiensis* most effective against autumn gum moth and other lepidopteran forest tree pests.

Biological control

Autumn gum moth offers considerable potential for some form of biological control being included into an IPM program. A viral epizootic causing high levels of mortality of late instar larvae was observed at Loxton. Preliminary work on isolating and characterising the virus has begun and future work should focus on the suitability of this pathogen for development into a bioinsecticide.

A number of egg and larval parasitoids have been recorded from autumn gum moth (de Little 1981; Elliott and Bashford 1978; Schumacher 1997). These include a scelionid egg parasite, *Telenomus* sp. (Hymenoptera: Scelionidae), several ichneumonid and braconid larval and pupal parasitoids and an unidentified species of tachinid fly.

Schumacher (1997) studied the parasitoid complex of autumn gum moth at Lyneham Ridge in 1993. *Telenomus* sp. was the only egg parasitoid found and it parasitised 14% of the autumn gum moth eggs laid in 1993. A large proportion of eggs laid early in the season were not affected due to low numbers of *Telenomus* sp. that contrasted with very high rates of parasitism late in the season when *Telenomus* sp. was more abundant. Two parasitoids, a new species of *Glyptapanteles* (Hymenoptera: Ichneumonidae) and *Casinarina micra* Gauld (Hymenoptera: Braconidae) were found parasitising larval autumn gum moth. Both species emerged from 4th instar larvae, but only accounted for 4 deaths out of 426 larvae. About 10% of autumn gum moth pupae were parasitised by *Heteropelma scaposum* Morely (Hymenoptera: Ichneumonidae). *H. scaposum* is a common parasite of numerous Lepidoptera including the agricultural pests *Helicoverpa armigera* (Hubner) and *Spodoptera litura* F. (Lepidoptera: Noctuidae).

It has been hypothesised that autumn gum moth outbreaks are at least partly a result of populations of the moth escaping in space from its parasitoids. However, there is little direct evidence for this. If parasitism is important in controlling autumn gum moth populations, then the mass rearing and release of parasitoids early in an outbreak may be a useful adjunct to other control options. The egg parasite *Telenomus* sp. would probably be the best initial candidate for such an approach since it attacks eggs and this reduces the number of damaging larvae.

A number of parasitoids have been associated with the leafblister sawfly, *P. frogatti* Riek (Hymenoptera: Pergidae). Thumlert and Austin (1994) recorded 17 species of which eleven were primary parasitoids and three were facultative parasitoids. The remaining three species had undetermined host relationships. However, species of the facultative hyperparasitoid genus *Cirrospilus* Westwood (Hymenoptera: Eulophidae) and the braconid *Bracon phylacteophages* Austin (Hymenoptera: Braconidae) are normally the most common parasitoids associated with leafblister sawfly. In Adelaide parasitism rates ranging from 15.6% to 60.3% have been recorded, with *C. margiscutellum* (Girault) by far the most common species and *B. phylacteophages* the next most common (Thumlert and Austin 1994), whilst in Melbourne the later species was more abundant (Farrell and New 1980). Both *B. phylacteophages* and *C. margiscutellum* are solitary primary parasitoids of third instar to early stage pupae of *P. frogatti*. *Cirrospilus margiscutellum* is also a hyperparasite of *Bracon* spp. and other parasitoids of the sawfly. Two *Bracon* species, *B. phylacteophages* and *B. confusus* Austin, have been used successfully in New Zealand for the control of leafblister sawfly (Austin and Faulds 1989).

During this study leafblister sawfly caused only minor damage to trees in one region. However, over its native range it is considered a pest of ornamental and plantation eucalypts (Mayo *et al.* 1997) and has become a damaging pest where it has been introduced into areas outside of its native range. Programs aimed at limiting the damage caused by leafblister sawfly within its native range will need to take into account the mortality caused by its parasitoids.

Challenges

Methodology

Insecticide exclusion treatments

Quantification of the impact of insect damage on tree growth requires the establishment of trials with treatments with and without insect feeding. The treatment without insect feeding is normally achieved by frequent application of insecticide. This was achieved at Lyneham Ridge due to its proximity to our laboratories in Canberra. However, it was only partially achieved at the Shepparton and Mildura trials due to distance of travel and cost of frequent visitation and treatment. The value of the data from these trials, in terms of quantifying the impact of insect damage, was reduced because complete exclusion was not achieved. The design and execution of replicated insect exclusion experiments are costly both in terms of establishment and operating cost. However, they are the most powerful way to produce the data needed to resolve the types of questions this report addresses (Hairston 1989). By applying insecticide throughout a trial, even when insect damage is low, the best result in terms of data integrity can be obtained.

Phytotoxicity

Possible phytotoxic effects of insecticide spraying were observed early in all insect exclusion trials. When insect damage was minimal, mean plant growth rates tended to be greater in unsprayed treatments than in sprayed treatment and the only plausible explanation for this was damage by insecticides in the sprayed treatment.

While insect exclusion experiments are commonly used in ecology to determine impacts of insects on plants (Crawley 1997), the possible detrimental effects on the plants from using such strong poisons must always be considered. Phytotoxic effects always remain a concern and occasionally insecticide treatments can produce quite unexpected results. Lonsdale and Farrell (1998) found that the exclusion of the biological control agent *Neurostrota gunniella* Busck (Lepidoptera: Gracillariidae) from its target weed *Mimosa pigra* resulted in decreased seed output by the plant. They concluded that the insecticide, carbofuran, used to exclude the moth also inhibited native pollinating insects. This, rather than the reduction in moth numbers, was thought to be the reason for the decrease in seed production on the sprayed plants. The phytotoxic effects seen in the current study, while small and apparently limited to the early establishment phase of the plantations, still raise some issues about how insecticides are used in controlling insect damage. Injudicious application of insecticides in young plantations may cause more harm than good.

Effective IPM systems should mostly eliminate the need for precautionary spraying. However, a better understanding of the impacts of insecticides on growth of young eucalypts would be useful. Designing and executing an experiment that included an insect exclusion treatment that did not use insecticides would be very difficult in Australia. The most reasonable alternative may be a meta-analysis approach in which growth rates of sprayed and unsprayed species of eucalypts in Australia are compared with similar species grown overseas where insect damage levels are nonexistent or minimal.

Costs of monitoring and maintaining experiments

Limits of time and resources restrict the frequency of visitation to each trial. Except for Lyneham Ridge, a minimum of two days was required for travel to and from sites. At Lyneham Ridge, visitation frequency increased leading up to periods of expected insect abundance which allowed insecticide application to be timed to have maximum effectiveness based on these observations. The frequency of visits also allowed more detailed information to be collected on the biology of pest species. At Shepparton, spraying occurred at fixed intervals. The interval between spraying was based on the insecticide manufacture's recommendations and experience of the effectiveness of the insecticides in the field. The level of insect population suppression at Shepparton varied more than at Lyneham, Ridge but was generally satisfactory. At Shepparton, there was also more chance for establishment of pest populations to be missed if they built up between visits. This meant that the opportunity to study the early phases of development of a pest population was not available.

Large trials with no insect exclusion

The Deniliquin species trials were designed as seed orchards to ultimately provide a source of genetically improved seeds. Consequently, they contained a large number of provenances and families. Although this is a standard approach in forestry tree improvement programs, there can be difficulties using these trials to screen for insect resistance. The lack of an insect exclusion treatment or control is the most significant concern. Insecticide treatments allow quantification of the inherent growth potential of the plant when free of insect damage, without which it is difficult to form conclusions on insect resistance. It can also be difficult to analyse and interpret the significance of insect damage impacts without an insecticide treatment. For example, large differences in insect resistance are meaningless from a silvicultural viewpoint if they have no impact on growth. Without control trees to provide inherent growth rates such determinations are not possible.

In summary, seed orchards can provide information on variation in levels of insect damage to a wide variety of genetic material. As such they may be useful in selecting a subset of trees for use in more detailed studies of damage impacts using insect exclusion experiments.

Economics of insect damage

A modelling approach

Due to some of the problems discussed in the previous section, the data available to carry out an economic analysis of the impacts of insect damage on plantation eucalypts was limited. To make best use of what data were available, as well as accessing data on insect impacts from the literature, a modelling approach was taken. As a desk top study (with only one site inspection in the Murray Valley), the purpose of this work was to explore the issues based on realistic plantation regimes. This approach has provided an indication of the gaps in data, information and knowledge, and has stimulated consideration of a range of important issues associated with insect management in eucalypt plantations.

By combining a plant growth model and a financial analysis model (*Sylva Ento Model*) existing data from the growth trials (see growth results in Chapters 2–4) could be used to calibrate the plant model and inform the design of realistic damage scenarios to impose upon the growth model. Data from the insecticide exclusion treatments were used to adjust the model tree to show realistic growth patterns without defoliation. The data on growth of defoliated trees obtained in the trials were used to help calibrate parameters for compensatory growth in the model.

The plant growth model is still in its early phases of development, but within the limitations of our current knowledge, we believe it adequately describes how a eucalypt tree allocates resources and grows. By considering allocation of stored carbohydrates for growth and mechanisms of compensation after defoliation, it provides insights into how defoliation affects tree growth.

The main limitation to the plant growth model is a paucity of data in several critical areas of eucalypt growth and development that the model attempts to describe. Better data in some if not all of the following areas would improve the model and address some of its current limitations:

- biomass of different plant parts measured annually or biannually,
- seasonal changes in biomass allocation to different plant parts,
- effects of thinning on changes in biomass allocation to different parts,
- effects of herbivory on changes in biomass allocation to different parts,
- effects of fertilisation/irrigation on changes in biomass allocation to different parts,
- ontogenetic change in biomass allocation to different parts,
- stored carbon, and
- mechanisms of compensation.

While various models of eucalypt growth which have been developed used to predict site productivity (e.g., ProMod, CABALA, 3PG (Battaglia and Sands 1997; Landsberg and Waring 1997; Sands *et al.* 2000)), because they do not consider stored carbohydrates they are not suited for examining the effects of defoliation on productivity. By allowing simulation of leaf loss, the model has the potential to be a useful management tool in various applications. For example, it could be used to optimise management regimes. By simulating various thinning and pruning regimes for saw log plantations it would be possible to determine what the reduction in stocking and canopy does to productivity. In the past, it has been assumed that there is a lag as the trees expand their crowns to utilise the site, but the timing and mechanisms are not well known. As far as testing anything that damage a tree, such as browsing, its usage is only limited by the imagination of those using it. For example, it could test intervention thresholds where there are different spatial arrangements of the damage. At a given level

of damage do scattered patches of damage differ in impact from discrete damage patches, and if there are differences at what point do control options need to be addressed.

There is little published data on the impact of insect damage over the commercial life of a plantation. Normally studies of the impact of insect damage measure growth in the immediate period (usually one to two years) after the damage event. However, because of compensatory growth (Trumble *et al.* 1993) projections of wood loss over the life of a plantation based on growth increment suppression one to two years after a damage event are unlikely to be accurate. By using a modelling approach to investigate insect attacks, we were able to see how plantations might respond to damage over the nominal rotation time. Of particular interest are the model predictions about the potential role of compensatory growth and thinning in plantation recovery from insect damage. Over longer rotation periods (i.e. >15 years) the model suggests that selective thinning of poorly performing trees may be a viable management strategy.

The *Sylva Ento Model* was developed based on a dynamic discussion of inputs and desired model abilities. It aimed to be able to apply economic analysis to insect damage scenarios impacting on a series of plantation management regimes and it brought together a wide range of information on plantation tree and wood attributes. In the absence of complete set of information for all parameters a range of assumptions and best estimates were used. The model strengths are that it gives a broad range of management options and generates outcomes and that it has a high degree of flexibility. Its weaknesses: are that some of the key inputs are based on incomplete data and that it has not been formally validated.

As is the nature of a desktop simulation, as many questions were raised as were answered. Some areas of future work identified were:

- Research to look at tree response to management practises such as irrigation, fertiliser and how they relate to the plant growth model. If this can be done, then there is the potential to use the model to look at topics such as nutrient deficiencies and how they relate the tree photosynthesis.
- Development of a single plant-economic model. This would remove the need for many of the standard data tables while delivering a high degree of flexibility.
- Expand and calibrate the plant growth model so that it could be used to predict productivity based on local radiation levels and including cloud cover conditions. In far north Queensland the sugar industry measures sugar content in the crops and relates that to each season's radiation levels—has it been a cloudy one or not. Expanding on such an approach the model could look at the impact of cloudy years on tree growth at different stages of growth.
- Investigate how biomass allocation interacts with tree architecture so as to refine at what point the crown starts to retreat. The interaction is affected by stocking rates and needs to be taken into account by the plant growth model.

Financial analyses

In the absence of management intervention options plantation standing volume for age was variously affected by insect attack, although generally the tested plantations showed recovery of production after insect damage. However, by the end of the nominal rotation periods there were differences between *E. grandis* and *E. globulus* plantations in post insect damage production recovery. This was the case across the fifty different damage scenarios tested.

Ranking mean annual increment (MAI) and internal rate of return (IRR) for different levels of insect damage showed that in all cases, given fixed financial inputs to plantation management, as MAI decreases, so does IRR. The effect of insect damage on MAI and IRR also varied between the two

plantation species with impact appearing to be greater on *E. globulus* than *E. grandis* plantations. It is suspected that it was the longer rotation period and the management regime (including thinning) of the *E. grandis* plantation, rather than the tree species, that combination to contribute to the greater recovery of MAI and reduced IRR sensitivity.

The addition of insect management had little impact on the IRR of the *E. grandis* plantation, where as it had a larger impact on the IRR for the *E. globulus* plantation. The impact of adding insect control to monitoring had little impact on IRR for both plantation regimes.

Management strategies

When to control

Currently the cost of insect control through the use of insecticides is relatively cheap compared to other plantation management inputs. Such low costs may lead to a situation where, rather than monitoring insect damage and attacking accordingly, spraying occurs automatically at any sign of insect pests or damage. There are, however, inherent risks in such an approach. If an automatic spray option is taken, particularly without the use of selective insecticides, effectively all insects, both beneficial and pest may be removed from the plantations. There may be some potential for beneficial insects to remain in retained native vegetation although issues like spray drift would need to be addressed. If natural control of insect pests is lost because beneficial insects are unable to recover from spraying, then the available for further pest control options are restricted. Effectively the plantation management regime is locked into insecticide application as the only option for pest control. This may be acceptable if the management options (insecticides and application techniques) remain unchanged.

Insecticide options and/or restriction of application methods could place added cost pressure on the plantation. Public pressure (i.e. proximity to other land uses), a significant mishap, new information, or some other unexpected or unplanned for cause may result in aerial applications being restricted. Consider one of the management scenario tested in Chapter 7—management scenario 3 for *E. globulus* where there was early summer 30% defoliation at age 3 years. At 30% defoliation a manager may choose to spray or not. If spraying does not occur and defoliation reaches 80% in late summer, IRR will go from 10.8% to 6.8% (a loss of 37%) with monitoring. If spraying is done with fixed wing application at \$20/ha (based on an experienced aerial contractor (Blyth 2002)), and is successful in controlling the insect pest, then IRR goes from 10.8% to 9.7% (a loss of 10.2%). If application is by helicopter at a cost of \$45/ha (based on de Little (2002)), then IRR goes from 10.8% to 9.6% (a loss of 11%). As shown, even when aerial application cost is more than doubled (from \$20/ha to \$45), there is little impact on IRR with (9.7% to 9.6%). Three year old plantation grown eucalypts are likely to be well over 7–8m tall. At this stage, it would be marginal whether or not an insect pest could be effectively treated from the ground. If insecticides could be applied from the ground at \$90/ha, application (Lawrence 2002), it would reduce IRR to 9.4%. Again, this is not a large change in returns. Where the trees are too tall for ground based spraying, stem injection may be an option. Assuming application costs of \$100/ha with 1000 stems/ha, and insecticide costs of \$20/ha, this will reduce IRR to 9.4%. In summary, with insect control ranging from \$20/ha through to \$120/ha, IRR goes from 9.7% to 9.4%

Even if returns are not sensitive to insecticide application costs, there is an important consideration. Aerial application of insecticides is very quick. Based on fixed wing application to broad acres, given the right conditions, 120 to 150ha/hr/plane can be treated. Ground based application could treat between 1 and 2ha/hr/unit. Ground based stem injection could treat approximately 0.6ha/hr/person. Therefore, depending on the labour force and equipment available, any ground based operation would be much slower than an aerial operation. If there is only a short window of time between detecting a pest outbreak and treating it effectively, such as in management scenario above, ground based applications may be ineffective in reducing defoliation. Therefore, it is critical that the option to use aerial application of insecticides is available and used appropriately.

IPM and monitoring

Plantation managers can choose to take either a proactive, or a more hands off approach, to management. Proactive pest management can include an Integrated Pest Management (IPM) system, where management actively seeks to understand the insect pest risk, monitor populations and respond in the most appropriate way at the most appropriate point in the pest damage/life cycle. Elliott *et al.* (1992) have described an IPM system for *Chrysophtharta bimaculata* (Tasmanian eucalypt leaf beetle) which includes population monitoring, an understanding of when best to treat, including at what stage the pest insect is vulnerable to natural enemies and other control options. Similarly, Steinbauer and Floyd (2000) report on a system of risk assessment for autumn gum moth that allows the manager to rate the risk to discrete plantation areas. The aim should be to focus attention and resources on those areas likely to need attention.

de Little (2002) likens regular monitoring of plantations to a regular medical check up to identify problems as soon as possible so as to allow early intervention. Management decision can include the intensity and method of monitoring. Monitoring of plantations is a critical part of IPM. Any automatic spraying in the absence of a monitoring program could raise the following issues:

1. It is wasting resources.
2. It eliminates natural enemies
3. It is exposing the plantation investment to potentially unnecessary risk (i.e. the risk of an accident, loss of natural pest control or development of insecticide resistance).
4. If questioned (from a public relations point of view), there would be little justification for the activity. Aerial application of any product is a very visible operation that draws attention from an increasingly aware public.

Monitoring, however, does place increased economic pressure on plantation returns. Considering *E. globulus* management scenario 4, and defoliation scenario 26 (see Chapter 7, this report), the addition of monitoring lowered IRR by 6% (8.4% to 7.9%). It is therefore important that monitoring is as cost effective as possible. Taking de Little's medical analogy (de Little 2002), monitoring should be treated as a package, with a range of issues covered by any inspection. For example, plantation inspection for fire season preparation, nutrient assessment, or weed inspections could include insect pest monitoring.

In order to make a monitoring program more efficient, knowledge of pest insect life cycles is required to ensure correct timing. Monitoring should be carried out through out the full plantation rotation. A single 100% defoliation at age 5 for *E. globulus* reduces IRR from 10.8% to 5.6% (by 48.1%). If a plantation has had insect attack and resources are limited, it should become a priority for continued surveillance as the impact of subsequent attacks can be more significant than a once off attack. Repeated defoliation has a greater impact on MAI and IRR than single defoliation events.

Final conclusions and recommendations

Insect exclusion studies demonstrated an 11% loss of volume in *E. grandis* at six years of age as a consequence of low to moderate defoliation by autumn gum moth and brown lace lerp and 18% loss of volume of *E. globulus* at five years following light to moderate damage from autumn gum moth and Christmas beetles. The loss of volume for *E. grandis* provenances ranged from 7% to 41% and from 0.5% to 56% for *E. globulus* provenances. Productivity losses of this magnitude resulting from light to moderate defoliation are broadly consistent with other studies of the impact of eucalypt defoliation.

Further increases in the amount of insect damage are anticipated in the Murray Valley as the total area planted to eucalypts increases and the abundance of pest insects increases concomitantly. Trends of

this type have been observed in Western Australia with the intensification of plantation forestry. It is not possible to definitively link increased insect damage to increased plantation area. However, this relationship is highly probable. Therefore, it is anticipated that plantation managers are likely to need to invest more in pest management in coming years than in the past.

Plantation managers will need a range of management options to utilise in different circumstances, depending on surrounding land-uses, magnitude of risk and community attitudes. Currently insect control options using aerial application of insecticides are relatively cheap. The modelling of plantation economic demonstrated that the addition of insect management had little impact on the IRR of the *E. grandis* plantation, although it had a larger impact on the IRR for the *E. globulus* plantation. For example under realistic control scenarios, the cost of spraying resulted in losses in IRR of around 10%. However, experience in other regions suggests that chemical intervention, particularly using aerial application and broad-spectrum insecticides, is likely to be challenged by local communities. Freedom to operate and successful management of eucalypt plantations is likely to require a diversity of management options including effective and efficient non-chemical methods. Currently, these options do not exist and need to be developed urgently.

Deployment of trees expressing superior insect resistance is one non-chemical option for pest management with some potential. Results presented in this report indicate significant potential for choosing tree species with higher resistance to insect attack (*Corymbia maculata*) than species such as *E. grandis* and *E. globulus* in the Murray Valley. Significant differences in resistance also were demonstrated among provenances within species such as *E. benthamii*, *E. grandis* and *E. globulus*. The path to adoption for these observations would require integration of insect resistance traits into a comprehensive breeding strategy. Given the importance of other traits such as growth rate, form and fibre quality, the best approach may be to screen and select for superior insect resistance from breeding lines that have already been developed. However, before insect resistance would be incorporated into a breeding strategy, a detailed understanding of the economic benefits of resistance under a range of levels of defoliation risk would need to be known.

Although it is not necessary to know the mechanisms of resistance of superior trees, knowledge of mechanisms can lead to much greater efficiencies in screening for resistant genotypes. It is recommended that any future work on insect resistance in eucalypts be done using insect exclusion trials coupled to laboratory experiments. Because of the relatively high cost of such investigations, it is suggested broad scale screening for possible resistance be followed by small focused experiments conducted at sites close to the home base of the research unit or at research stations with staff available to assist in monitoring and trial maintenance. The findings in these trials would need to be verified in the laboratory using oviposition and feeding trials, and preferably manipulation experiments to determine the mechanism of resistance.

While most research into the non-insecticidal control of insect damage to eucalypt plantation has been directed towards identify and characterising plant resistance, plant tolerance to damage has until recently been overlooked. For resource-rich environments, fast growing species that can tolerate insect damage may be better suited than slower growing, chemical defended species. This may be particularly so for plantations with long plantation times (> 15 years) where there may be sufficient time for compensatory growth to balance productivity losses due to insect attack. This was borne out by the economic analysis which indicated that the longer rotation time of *E. grandis* plantations resulted in greater MAI recovery and reduced IRR sensitivity in response to insect attack compared to *E. globulus* plantations which had the shorter rotation times. The economic analysis results also suggested that the possible benefits of selecting thinning as a management response to insect damage also needs to be investigated.

Other non-chemical management options that require further consideration are biological control methods, either by encouraging natural enemies or by introduction of natural enemies into a plantation at an appropriate time. The former approach is likely to be more practical in the short-term. Natural enemies could be encouraged by planting of other plant species as food sources or by enhancing the

structural or floristic diversity of plantations. These options need to be integrated with other silvicultural practices to ensure that plantation management is both cost-effective and practical.

Silvicultural control options also need to be investigated. It is possible that varying the spacing, pruning, fertiliser regime, weed control practice and layout of plantings could reduce the amount of insect damage in a plantation. The effects of these practices on key pest species are almost entirely unknown and warrant urgent attention.

The importance of pest management in eucalypt plantations in the Murray Valley is likely to increase with the increased intensity of plantation establishment. At the same time, community attitudes towards the use of chemical control options are likely to continue to impinge upon the choices of plantation managers. Non-chemical options for management of the key pests do not exist and need to be developed urgently as the issue in the future is not just going to be maximising profits by minimising losses to pests and diseases, but ensuring continued freedom to operate in a diverse rural landscape. Having the right information to make pest control decisions in such a rapidly diversifying operating environment is essential. Further development of a system like the *Sylva Ento Model* to more easily allow simulation modelling for decision management would be a useful addition to the plantation manager's tool kit.

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Appendix 1 Plantation management regimes

Eucalyptus globulus pulpwood production

Table A1.1 Plantation management regime

Stocking		Initial (stems/ha)	Finish (stems/ha)	Removed (stems/ha)	Cumulative (stems/ha)
Establishment	Year	1100	1000	100	100
Year 10	10	1000	0	1000	1100
Volume		Initial (m ³ /ha)	Finish (m ³ /ha)	Removed (m ³ /ha)	Cumulative (m ³ /ha)
CF	10	300.0	0.0	300.0	300.0

Table A1.2 Physical products and conversion factors

Physical products						
Products	Year	Waste (m ³ /ha)	Pulpwood (m ³ /ha)	Sawlogs (m ³ /ha)	Veneer (m ³ /ha)	Total (m ³ /ha)
CF	10	0.0	300.0	0.0	0.0	300.0
					Total	300.0
					MAI	30.0
Conversion factor						
	Year	10				
	(gmt/m ³)	1.1760				
Products		Waste (GMT/ha)	Pulpwood (GMT/ha)	Sawlogs (GMT/ha)	Veneer (GMT/ha)	Total (GMT/ha)
Operation	Year					
CF	10	0.0	352.8	0.0	0.0	352.8

Table A1.3 Financial budgets

Expenses							
Harvest to roadside		Volume removed	Weight removed	Stems removed	Mean tree	Costs	
Operation	Year	(m ³ /ha)	(GMT/ha)	(Stems/ha)	(m ³ /stem)	\$/GMT	\$/ha
CF	10	300.0	352.8	1 000	0.30	\$20.00	\$7 056.05
Total		300.0	352.8	1 000			
Transport		Waste	Pulpwood	Sawlogs	Veneer		
	Distance	(km)	(km)	(km)	(km)		
	Truck	0.0	30.0	30.0	30.0		
	Rail	0.0	220.0	0.0	0.0		
		Truck	Rail				
		(\$/t/km)	(\$/t/km)				
	Rate	\$0.10	\$0.05				
Operation	Year	Waste	Pulpwood	Sawlogs	Veneer	Total	
CF	10	(\$/ha)	(\$/ha)	(\$/ha)	(\$/ha)	(\$/ha)	
		\$0.00	\$4 939.23	\$0.00	\$0.00	\$4 939.23	
Returns							
Operation	Year	Waste	Pulpwood	Sawlogs	Veneer		
CF	10	(\$/m ³)	(\$/GMT)	(\$/m ³)	(\$/m ³)		
		\$0.00	\$69.79	\$80.00	\$110.00		
Operation	Year	Waste	Pulpwood	Sawlogs	Veneer	Total	
CF	10	(\$/ha)	(\$/ha)	(\$/ha)	(\$/ha)	(\$/ha)	
		\$0.00	\$20 935.91	\$0.00	\$0.00	\$20 935.91	

Eucalyptus grandis* sawlog production*Table A1.4** Plantation management regime

Stocking		Initial (stems/ha)	Finish (stems/ha)	Removed (stems/ha)	Cumulative (stems/ha)
Establishment	Year	1100	1 000	100	100
NCT	2	1 000	666	334	434
Year 6	6	666	444	222	656
Year 10	10	444	222	222	878
Year 20	20	222	0	222	1100
Volume		Initial (m ³ /ha)	Finish (m ³ /ha)	Removed (m ³ /ha)	Cumulative (m ³ /ha)
T1	6	81.2	54.7	26.5	26.5
T2	10	174.5	96.1	78.5	105.0
CF	20	394.4	0.0	394.4	499.4
Pruning		Number (stems/ha)	Height (m)		
Lift 1	2	400	3		
Lift 2	4	230	8		

Table A1.5 Physical products

Products	Year	Waste (m ³ /ha)	Posts (m ³ /ha)	Pulpwood (m ³ /ha)	Sawlogs (m ³ /ha)	Veneer (m ³ /ha)	Total (m ³ /ha)
T1	6	0.0	0.0	23.9	0.0	0.0	23.9
T2	10	9.0	0.0	44.8	35.8	0.0	89.6
CF	20	38.6	0.0	77.2	193.1	77.2	386.1
						Total	499.6
						MAI	25.0
Conversion factor							
Year		6	10	20			
(GMT/m ³)		1.1633	1.1760	1.1914			
Products		Waste (GMT/ha)	Posts (GMT/ha)	Pulpwood (GMT/ ha)	Sawlogs (GMT/ ha)	Veneer (GMT/ ha)	Total (GMT/ ha)
Operation	Year						
T1	6	0.0	0.0	27.8	0.0	0.0	27.8
T2	10	10.5	0.0	52.7	42.1	0.0	105.4
CF	20	46.0	0.0	92.0	230.0	92.0	460.0

Table A1.6 Financial budgets

Expenses							
Harvest to roadside		Volume removed	Weight removed	Stems removed	Mean tree	Costs	
Operation	Year	(m³/ha)	(GMT/ha)	(Stems/ha)	(m³/stem)	\$/GMT	\$/ha
T1	6	23.9	27.8	222	0.11	\$17.00	\$472.02
T2	10	89.6	105.4	222	0.40	\$15.00	\$1 580.56
CF	20	386.1	460.0	222	1.74	\$12.00	\$5 519.96
Total		499.6	593.1	666.0			
Transport							
	Distance	Waste (km)	Pulpwood (km)	Sawlogs (km)	Veneer (km)		
	Truck	0.0	30.0	30.0	30.0		
	Rail	0.0	220.0	0.0	0.0		
	Rate	Truck (\$/t/km)	Rail (\$/t/km)				
		\$0.10	\$0.05				
Operation	Year	Waste (\$/ha)	Pulpwood (\$/ha)	Sawlogs (\$/ha)	Veneer (\$/ha)	Total (\$/ha)	
T1	6	\$0.00	\$388.72	\$0.00	\$0.00	\$388.72	
T2	10	\$0.00	\$737.60	\$126.45	\$0.00	\$864.04	
CF	20	\$0.00	\$1287.99	\$690.00	\$276.00	\$2 253.98	
Returns							
Operation	Year	Waste (\$/m³)	Pulpwood (\$/GMT)	Sawlogs (\$/m³)	Veneer (\$/m³)		
T1	6	\$0.00	\$52.70	\$0.00	\$0.00		
T2	10	\$0.00	\$56.35	\$70.00	\$0.00		
CF	20	\$0.00	\$76.86	\$80.00	\$110.00		
Operation	Year	Waste (\$/ha)	Pulpwood (\$/ha)	Sawlogs (\$/ha)	Veneer (\$/ha)	Total (\$/ha)	
T1	6	\$0.00	\$1257.84	\$0.00	\$0.00	\$1 257.84	
T2	10	\$0.00	\$2524.43	\$2 508.81	\$0.00	\$5 033.24	
CF	20	\$0.00	\$5934.91	\$15 444.13	\$8 494.27	\$29 873.30	

Plantation establishment and management

Table A1.7

	Operation	Year	(\$/gross planted ha)
Establishment	Supervision	0	\$20.00
	Site design, mapping and layout	0	\$20.00
	Firebreaks and dams	0	\$0.00
	initial broadcast weed control	0	\$60.00
	Ripping and mounding	0	\$180.00
	Tail drain preparation	0	\$25.00
	Browsing animal control	0	\$4.00
	Planting stock	0	\$300.00
	Planting	0	\$135.00
	Assessment stocking	0	\$15.00
	Post plant weed control	0	\$125.00
	Fertiliser	0	\$140.00
	Refilling	0	\$400.00
Year 1 maintenance	Supervision	1	\$10.00
	Firebreaks and dams	1	\$20.00
	Assessment—general inspection	1	\$10.00
	Assessment—growth	1	\$15.00
	Assessment—nutrients	1	\$39.00
	Noxious weeds control	1	\$10.00
	Roads and tracks	1	\$20.00
	Fertiliser (aerial)	1	\$210.00
	Fertiliser (ground)	1	\$215.00
	Broad cast weed control	1	\$150.00
Year 2 maintenance	Supervision	2	\$10.00
	Assessment—general inspection	2	\$8.00
	Assessment—growth	2	\$15.00
	Roads and tracks	2	\$20.00
Post year 2 maintenance	Supervision	Each	\$5.00
	Assessment—growth	10	\$8.00
	Assessment—nutrients	10	\$26.00
	Roads and tracks	Each	\$20.00
	Roads for harvesting	5	\$200.00
Overheads	Insurance	Each	\$25.00
	Land lease/rent	Each	\$0.00

Table A1.8

Operation	Year	\$/unit	Units
Irrigation water	Each	\$30.00	MI
Irrigation labour	Each	\$25.00	Hour
Non commercial thinning	2	\$0.50	Trees
Pruning—first lift	2	\$0.75	Trees
Pruning—second lift	4	\$1.50	Trees
Pruning—third lift	0	\$0.00	Trees

Appendix 2 Defoliation scenarios

Table A2.1 Defoliation scenarios imposed upon plant growth model. Winter defoliation occurred from March to June/July, spring defoliation from September to November and summer defoliation in December (early) and February (late). Note that 100% defoliation equates to 100% leaf loss.

Scenario	Description											
	First attack			Second attack			Third attack			Forth attack		
	Season	Age	Defoliation	Season	Age	Defoliation	Season	Age	Defoliation	Season	Age	Defoliation
S 0	Nil damage											
S 1	Winter	1	30%									
S 2	Spring	1	30%									
S 3	Early summer	1	30%									
S 4	Late summer	1	30%									
S 5	Winter	3	30%									
S 6	Spring	3	30%									
S 7	Early summer	3	30%									
S 8	Late summer	3	30%									
S 9	Winter	1	80%									
S 10	Spring	1	80%									
S 11	Early summer	1	80%									
S 12	Late summer	1	80%									
S 13	Winter	3	80%									
S 14	Spring	3	80%									
S 15	Early summer	3	80%									
S 16	Late summer	3	80%									
S 17	Winter	1	100%									
S 18	Spring	1	100%									
S 19	Early summer	1	100%									
S 20	Late summer	1	100%									
S 21	Winter	3	100%									
S 22	Spring	3	100%									
S 23	Early summer	3	100%									
S 24	Late summer	3	100%									
S 25	Winter	1	10%	Winter	2	100%						
S 26	Winter	1	30%	Winter	2	100%						
S 27	Winter	1	10–20%	Winter	2	10–20%	Winter	3	10–20%	Winter	3	10–20%
S 28	Spring	1	10–20%	Spring	2	10–20%	Spring	3	10–20%	Spring	3	10–20%
S 29	Early summer	1	10–20%	Early summer	2	10–20%	Early summer	3	10–20%	Early summer	3	10–20%

Scenario	Description											
	First attack			Second attack			Third attack			Forth attack		
	Season	Age	Defoliation	Season	Age	Defoliation	Season	Age	Defoliation	Season	Age	Defoliation
S 30	Late summer	1	10–20%	Late summer	2	10–20%	Late summer	3	10–20%	Late summer	3	10–20%
S 31	Early summer	1	30%	Late summer	1	80%						
S 32	Early summer	3	30%	Late summer	3	80%						
S 33	Winter	4	30%									
S 34	Winter	4	100%									
S 35	Winter	4	100%	Winter	5	80%						
S 36	Early summer	1	100%									
S 37	Early summer	2	100%									
S 38	Early summer	3	100%									
S 39	Early summer	5	100%									
S 40	Early summer	10	100%									
S 41	Winter	2	100%									
S 42	Winter	2	100%	Winter	3	100%						
S 43	Winter	2	100%	Winter	3	100%	Winter	4	100%			
S 44	Winter	2	100%	Winter	3	100%	Winter	4	100%	Winter	5	100%
S 45	Winter	2	100%	Winter	4	100%						
S 46	Winter	2	100%	Winter	5	100%						
S 47	Winter	2	100%	Winter	9	100%						
S 48	Winter	3	100%	Winter	4	100%						
S 49	Winter	3	100%	Winter	5	100%						
S 50	Winter	3	100%	Winter	9	100%						

Appendix 3 Manuscript from the project

Genetic variation in growth of *Eucalyptus grandis* grown under irrigation in south eastern Australia

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Abstract

Within and between provenance variation in growth to age 4½ years of *Eucalyptus grandis* Hill ex Maiden was investigated in three irrigated provenance-family trials at two localities (Shepparton and Koorlong) in the Murray Valley and in a similar trial at Werribee in southern Victoria. These contained 53 seedlots representing both natural stand provenances and genetically improved material from a total of 15 sources.

Height growth was mediocre to poor, possibly due to water stress with site averages ranging from 1.4 m per year to 2.4 m per year. At the provenance level significant variation in growth traits was found at all sites. Plantation select material from Loxton SA and material from a seed orchard at Coffs Harbour NSW generally showed the best growth over all sites. Growth of unimproved natural provenances was comparable at only one site, Shepparton.

At three of the four sites there were significant differences between families for various growth traits. Estimates of individual tree heritability for growth traits ranged from very low (0.06) to moderate (0.21). With combined data from all sites, both provenance and family-within-provenance differences proved significant for all growth traits. In contrast, environment (trial site) by provenance and environment by family-within-provenance interactions for growth traits were not significant across the sites.

The results are discussed in terms of the importance of provenance selection for optimising *E. grandis* and the opportunities for genetic improvement in the species through selection.

Introduction

Eucalyptus grandis is one of the most widely planted eucalypts around the world. In Australia, strong interest developed in planting this species in the late '60s and early '70s, and the company Australian Paper Mills (APM) began establishing plantations of this species in the Coffs Harbour region of NSW. However, this interest faded and APM's plantations were subsequently sold off in the mid-1970s to State Forests of NSW (Matheson *et al.* 1996). More than 10 years later, field trials conducted by the Shell Company of Australia identified *E. grandis* as the best eucalypt available for establishment of fast growing pulpwood plantations over a wide range of coastal Queensland (Cromer *et al.* 1991). Though few plantations of the species were subsequently established, there is again increasing interest in planting this species in Australia. In addition, *E. grandis* is one of the key parent species from which hybrid combinations of eucalypts are currently being developed for a wide range of farm forestry and other sites in Australia (Harwood and Arnold 1999).

Insect predation in Australian *E. grandis* plantations has been an occasional but significant concern at various locations (R.B. Floyd pers. obs.), particularly with respect to potential impacts on both growth and stem form. Wingless grasshopper (*Phaulacridium vittatum* (Sjöstedt) Orthoptera: Acrididae) and

various melalonthine beetles have caused damage to trees at establishment while a wide range of insects have caused significant damage to saplings and trees. The most significant insect pests of established *E. grandis* include autumn gum moth (*Mnesampela privata* (Guenée) Lepidoptera: Geometridae), leafblister sawfly (*Phylacteophaga* spp. Hymenoptera: Pergidae), gumtree lerps (*Cardiaspina fiscella* Hemiptera: Psylloidea) and gumtree scale (*Eriococcus coriaceus* Maskell Hemiptera: Eriococcidae). The establishment pests and *E. coriaceus* can kill whole plants while the other pests may affect growth increment but rarely cause mortality.

In Australia, provenance trials of *E. grandis* were established in coastal regions of northern New South Wales at Wedding Bells State Forest (Coffs Harbour area) and at Timmsvale in 1972 by State Forests of NSW to test seed collected from sources across a wide altitudinal and latitudinal range (Burgess 1988). Further provenance trials were also established in 1982 at Wedding Bells SF near Coffs Harbour, NSW, and at Peachester, Queensland, with some later collections (Burgess 1988). More recently, several *E. grandis* trials have been established under irrigation in the southern Murray Darling Basin (MDB). At Loxton, South Australia, Land Energy Pty Ltd established a provenance trial in collaboration with Golden Choice Ltd. as part of a wastewater re-use plantation (Arnold *et al.* 1996). In 1991, CSIRO initiated an irrigated trial at Dubbo in 1991 to test 40 natural stand family seedlots collected as part of an inbreeding study (Burgess *et al.* 1996).

These earlier Australian trials, along with numerous ones overseas, have shown some of the most productive *E. grandis* provenances to be those from the northern part of New South Wales centred around Coffs Harbour (Burgess 1988; CABI 1998). However, in any one location there are typically also other provenances from geographically wide ranging and disparate parts of the species natural range that tend to perform well (CABI 1998). In addition, significant and marked differences in growth performance have often been noted between seedlots of the species obtained within one small geographic area (Matheson and Mullin 1987; Burgess 1988; Eldridge *et al.* 1993; Arnold *et al.* 1996; CABI 1998).

One factor that may contribute to variation between the growth and form of *E. grandis* when planted in southern Australia is its genetic variation in susceptibility to damage from defoliating insect pests (Floyd and Farrow 1994). A number of provenances of other species of eucalypts have been identified as having superior resistance to defoliating insect pests (Floyd *et al.* 1994; Farrow *et al.* 1994). Increasing insect resistance through selection and breeding can provide an environmentally sensitive approach to pest management that may, for *E. grandis*, be both effective and resilient if appropriately deployed.

In 1993–94 four *E. grandis* provenance-family trials were established across a range of effluent irrigated sites in south eastern Australia to evaluate seedlots from both natural stand provenances and improved sources. It was planned to use these trials to identify germplasm with superior resistance and/or tolerance to insect attack and provide a base from which to select more resistant material for ongoing breeding. The objectives of these trials included: (i) assessment of provenance and family-within-provenance performance with respect to economically important traits in *E. grandis* grown under (effluent) irrigation in the south eastern Australia; (ii) evaluation of genetic variation in the susceptibility and tolerance of *E. grandis* to defoliating insect pests; and (iii) identification of families and provenances which offer potential for future genetic improvement. This paper reports on variation between and within provenances for growth up to around age 4½ years in these trials, but not on variation in susceptibility or tolerance to defoliating insect pests. As of age 4½ years, insect predation in all four trials had been only minor and could not be considered a significant factor in growth or form performance. The significance of genotype by environment interactions in growth across the trial sites is also reported.

Methods

Trial sites and layouts

In December 1993/January 1994, *E. grandis* provenance-family trials were established at four sites in Victoria—two at Koorlong near Mildura, one near Shepparton and one near Werribee. Climatic parameters for these sites are provided in Table A3.1. The two sites at Koorlong (site A—34° 20' 4.4"S 142° 04' 36.9"E; and, site B—34° 20' 9.0"S 142° 04' 17.2"E; both approx. 30 m a.s.l.) are located within a 105 ha drip-irrigated waste water hardwood plantation approximately 6.5 km from Koorlong township in north western Victoria. The irrigation water comprises primary treated domestic and industrial wastewater from the Mildura/Irymple region. Trial site A at Koorlong is free-draining with a deep sandy loam (of 30 to 60 cm depth) overlying a clay formation. Trial site B at Koorlong has a heavier clay loam soil. Prior to establishment the soils at both sites were relatively alkaline (pH 8.0 to 8.5 at 20 cm depth). Site preparation consisted of ripping of planting lines to 60 cm depth and treatment of planting lines with pre-emergent herbicides. Tree spacing at both sites was 3m between rows and 2m between trees.

Table A3.1 Climatic parameters for the trials sites and climatic requirements for *Eucalyptus grandis* plantations.

Parameter	Koorlong	Shepparton	Werribee	Requirements for Viable Plantations *
Mean annual rainfall	276 mm	503 mm	546 mm	700–2500 mm
Mean annual temperature	23.4°C	15.4°C	14.3°C	14–25°C
Mean maximum temperature	31.3°C	31.1°C	26.0 °C	25–34°C
hottest month				
Mean minimum temperature	4.0°C	3.0°C	4.5°C	3–16°C
coldest month				
Absolute minimum temperature	–5.7°C	not available	not available	> –8°C
Annual evaporation	1801 m	not available	not available	not specified

* Source of data on “Requirements for Viable Plantations”: Booth and Pryor, 1991.

The trial at the Shepparton site (36°19' 13.5" S 145°23' 25.1" E, and 113 m a.s.l.) is located 10 km from Shepparton within a property belonging to Goulburn Valley Water. The trial is trickle irrigated with primary treated domestic and industrial wastewater from the Shepparton/Mooroopna region. Soil types are Goulburn Loam and Congupna Clay Loam and are categorised as grey-brown clay loams at 0–15 cm overlaying yellow-grey medium and heavy clays to 200 cm. The clay subsoils are dense and intractable and not a good medium for roots. Soils analysis revealed mean surface (to 25 cm) pH (H₂O) of 6.6. Deeper profiles from 25 to 200 cm ranged from pH (H₂O) of 7.5 to 8.3. Site preparation involved ripping to a depth of 60 cm followed by the application of gypsum at a rate of 5 ton/ha. Ripping was done using a “winged foot” ripper behind a bulldozer. Tree spacing was 3m between rows and 2m between trees.

The fourth trial near Werribee (approximately 37°59' S 144°38' 30" E, and 24 m a.s.l.) was located 7 km from the Werribee township within a property belonging to Melbourne Water. The trial was flood irrigated with primary treated domestic and industrial wastewater from metropolitan Melbourne. Soils were a heavy grey clay loam which prior to establishment of the trial was slightly acid (pH 6.0 to 6.5 at 20 cm). Site preparation consisted of levelling the site and ripping of planting lines. Tree spacing was 3m between rows and 2m between trees.

Seedlots

The four trials involved a total of 47 seedlots representing a total of 15 different provenances of *E. grandis* and 6 seedlots representing a single provenance of *E. saligna* (Table A3.2). At the time the trials were established this provenance of *E. saligna* was believed to be *E. grandis*. It was obtained from Blackdown Tableland which is an area where the distribution of the two species overlap. Though the populations in this area of central eastern Queensland are sometimes considered intermediate as they can be difficult to assign to either species, the adult phenotypes from seed obtained from these populations tend to segregate clearly towards either *E. grandis* or *E. saligna* (CABI 1998).

Three of the 15 provenances represented genetically improved seedlots. One was from a South African clonal seed orchard, and was brought into Australia in the 1980s. The second improved lot came from a seedling seed orchard established near Coffs Harbour by State Forests of New South Wales in the early 1980s. The third came from parent trees identified from intensive phenotypic selection at age 4½ years in a 20 ha irrigated *Eucalyptus grandis* plantation at Loxton S.A. Each of these three improved sources were represented only as multiple parent bulked seedlots.

Not all seedlots were represented at all sites (see Table A3.2).

Culture

Throughout their growth, the Shepparton trials have been irrigated at an average of 7.0 megalitre/ha/annum while the Koorlong sites received 7.6 megalitre/ha/annum (5.05–9.40 megalitre/ha/annum) of water. Similar rates were applied at Werribee. Post establishment weed control was limited to regular slashing.

Trial design

The two Koorlong trials and the one at Shepparton each comprised five complete replicates with rows and columns within replicates providing two-dimensional blocking within replicates. The trial at Werribee comprised six complete replicates in a randomised complete block design. The seedlots in each trial were represented as 4-tree row plots in each of the replicates.

Assessment

All surviving trees were assessed in mid-1998, at approximately 4½ years age, for height and diameter. Heights were measured to the nearest 0.1 m using height poles and diameter at breast height over bark (DBH) was measured with diameter tapes.

Analyses

The software package DataPlus 1.0 (Williams *et al.* 1997) was used to pre-process the data and screen for incorrect entries and outlying values. Extreme outliers were excluded from the analyses.

For analyses, individual conical tree volumes (dm³) were calculated using the following formula:

$$V = 0.333 * Ht * (3.14 * DBH^2 / 4)$$

where: V is individual tree volume in dm^3
 DBH^2 is the diameter at breast height over bark (dm) squared
 H_t is tree height (dm)

Plot means, variances and counts for height, DBH and volume were calculated by DataPlus. Analyses of variance were performed on plot mean data using GENSTAT 5.3.2 following procedures outlined by Williams and Matheson (1994).

Due to poor overall survival at Werribee, the trial could only be analysed for provenance effects. The survivals of many of the families established there were too low at age 4½ years for valid analyses at the family level.

Genetic parameters

Genetic parameters were estimated separately by site for the two trials near Koorlong and the one at Shepparton. Appropriate variance components for genetic parameter computation were obtained by mixed model analyses. These analyses were conducted using the REML procedure in GENSTAT 5.3.2. Only materials representing true single parent open-pollinated *E. grandis* seedlots were included in these analyses.

The mean family-within-provenance variance components, estimated across all the natural stand *E. grandis* provenances in each trial, were used to estimate mean within-provenance individual tree heritabilities (denoted h^2) as follows:

$$h^2 = 1/r * \sigma_f^2 / \sigma_p^2$$

where:

r = coefficient of relationship (taken to be 0.4 for families of eucalypts from natural stands)

σ_f^2 = variance between families-within-provenances

σ_p^2 = phenotypic variance
 $= (\sigma_f^2 + \sigma_m^2 + \sigma_t^2)$

σ_m^2 = variance between plots

σ_t^2 = variance between trees-within-plots (Williams and Matheson 1994, Chapter 6)

The coefficient of relationship used in computation of the individual tree heritabilities for these open-pollinated *E. grandis* families was taken as 0.4, rather than the value of 0.25 for half-sib families. Open-pollinated *E. grandis* families from natural stands generally carry a degree of inbreeding resulting from selfing and neighbourhood inbreeding, and thus can not be considered to be true half-sibs (Eldridge et al. 1993; Burgess et al. 1996).

Standard errors for the heritability estimates were calculated according to Becker (1984).

Genotype by environment interactions

The data (plot means) from the two trials at Koorlong and the one at Shepparton, excluding that of *E. saligna* material, were pooled for combined analyses across sites to examine the significance of genotype x environment interaction effects for *E. grandis*.

Table A3.2 Details of the *Eucalyptus grandis* and *E. saligna* seedlots established in the trials Koorlong, Shepparton and Werribee

CSIRO Seedlot No.	Species	No. of parent trees ¹ in bulk lot	Provenance details				No. of seedlots at each site							
			Location	Latitude (S)	Longitude (E)	Altitude (m asl)	Koorlong A		Koorlong B		Shepparton		Werribee	
							Bulk	Individ	Bulk	Individ	Bulk	Individ	Bulk	Individ
11159	<i>E. grandis</i>	4	Mt. George, NSW	31° 50'	152° 00'	300	1	0	1	0	0	0	0	0
11996	<i>E. grandis</i>	6	Bulahdelah, NSW	32° 25'	152° 10'	200	1	0	1	0	1	0	1	0
15120	<i>E. grandis</i>	10	Lake Cathie, NSW	31° 32'	152° 52'	10	1	0	1	0	1	0	1	0
15632	<i>E. grandis</i>	8	Woondum, QLD	26° 17'	152° 48'	100	1	0	1	0	1	0	1	0
16435	<i>E. grandis</i>	8	Wedding Bells SF, NSW	30° 09'	153° 07'	120	1	4	1	4	0	5	0	5
16437	<i>E. grandis</i>	15	Wahau Trig, NSW	30° 05'	153° 01'	300	1	5	1	5	0	6	0	6
16439	<i>E. grandis</i>	12	Orara SF, NSW	30° 11'	153° 08'	3	1	0	1	0	0	0	0	0
16442	<i>E. grandis</i>	-	Bruxner Park, NSW	30° 14'	153° 05'	200	0	5	0	5	0	6	0	6
16454	<i>E. grandis</i>	-	Pine Creek SF, NSW	30° 24'	153° 00'	150	0	6	0	6	0	5	0	5
16447	<i>E. grandis</i>	-	Langley's Rd, Coffs Harbour, NSW	30° 13'	152° 56'	630	0	6	0	6	0	6	0	6
18277	<i>E. grandis</i>	-	Bellthorpe, QLD	26° 52'	152° 42'	400	0	6	0	6	0	6	0	6
ERA-1 ²	<i>E. grandis</i>	1	Boambee, NSW	30° 18'	153° 03'	60	0	0	0	0	1	0	1	0
ERA-2 ²	<i>E. grandis</i>	100	Loxton, SA—plantation selects	34° 26'	140° 36'	30	1	0	1	0	0	0	0	0
18146	<i>E. grandis</i>	> 24 ³	Coffs Harbour Seedling Seed Orchard (SFNSW)	30° 08'	153° 07'	100	1	0	1	0	1	0	1	0
17803	<i>E. grandis</i>	Bulk ⁴	Clonal Seed Orchard— Pretoria, SOUTH AFRICA	- -	- -	- -	1	0	1	0	0	0	0	0
18229	<i>E. saligna</i>	-	Blackdown Tableland, QLD	23° 50'	149° 05'	880	0	6	0	6	0	6	0	6
TOTALS: Number of seedlots			- single parent tree				38		38		40		40	
			- multiple parent bulks				10		10		5		5	
			Number of provenances				14		14		12		12	

1 number of seed parent trees contributing to the bulk seedlot

2 these seedlots (ERA-1 and ERA-2) were not obtained through CSIRO.

3 the Coffs Harbour Seedling Seed Orchard seedlot comprised a multiple parent bulk seedlot made up of seed from 3 to 4 parent trees of each of the 24 families in the State Forests of NSW seed orchard at the time of collection.

4 this seedlot consists of an imported multiple parent bulk seedlot from a clonal seed orchard (number of parent trees uncertain) in South Africa.

Results

Survival and growth

High survivals were obtained in both Koorlong trials (approximately 85%) and at Shepparton (> 90%). At Werribee however, early problems with water logging as well as damage by rabbits and sheep resulted in patchy and poor survivals (43% overall) and only data from 3 of the 6 replicates could be used for the analyses reported here.

The best growth was obtained at Shepparton where tree height and volume averaged 10.7 m and 27.3 dm³ respectively at age 4½ years (Tables A3.3.1-A3.3.3). At Koorlong average growth was 30% or more lower than at Shepparton with 4½ year average heights in the two trials being only 7.4 m and 6.5 m. Growth at Werribee was relatively poor with height averaging only 5.8 m after 4½ years. At all four sites insect predation levels had been relatively light (<10% defoliation in any one year) and thus, considered not to have impacted significantly on growth obtained.

Provenance variation

Significant ($p<0.05$) provenance variation was found for height at Koorlong A, Koorlong B and Shepparton; for DBH at Werribee; and for volume at both Shepparton and Werribee (Table A3.4). In both Koorlong trials, the provenance that performed best for all growth traits was the one from the Plantation selects at Loxton (Tables A3.4.1-A3.4.3). Other provenances that performed well for growth in the same two trials included Lake Cathie, NSW, and the one from South Africa. The poorest *E. grandis* provenance for growth (height, DBH and volume) in both Koorlong trials was Orara SF, NSW. Growth of the single provenance of *E. saligna* included in the trials (Blackdown Tableland, QLD) was relatively poor at all four sites.

At Koorlong A, the Coffs Harbour seed orchard material also performed very well (ranked second for all growth traits). However, nearby in Koorlong B, its growth was poor. Subsequent inspections of the plots of this provenance in the latter trial revealed that those in three of the replicates had been adversely affected by tractor damage and some by irrigation dripper malfunction. Consequently, its performance in that trial must not be considered an accurate representation its genetic potential.

At Shepparton, Woondum was the best provenance for all growth traits. Others that performed similarly there included Bruxner Park, Buladelah and the Coffs Harbour seed orchard material. The poorest *E. grandis* provenances in the same trial were Bellthorpe and Wedding Bells provenances (ranked 11th and 12th for volume respectively). The Lake Cathie provenance, which had performed well at Koorlong, showed relatively poor growth at Shepparton ranking only 10th by volume.

At Werribee, the Coffs Harbour seed orchard material again grew well. It had the largest average height, DBH and volume there. Others with similar performance included Lake Cathie (2nd for volume) and Bruxner Park (3rd for volume). The Woondum provenance had the poorest growth of all the *E. grandis* provenances at Werribee.

The growth of the single *E. saligna* provenance was inferior to all the *E. grandis* provenances in the Koorlong A trial, and it was generally amongst the poorest *E. grandis* provenances in the other three trials. With the exception of the trial at Werribee, its rank for DBH and volume among the *E. grandis* provenances was somewhat higher than for height, suggesting that the species grows with more stem taper than most of the *E. grandis* on the same sites.

Of the *E. grandis* provenances represented at all four sites, no single provenance showed consistently superior performance. The Lake Cathie provenance ranked second or third best by volume at three

Table A3.3.1 Provenance means and (rankings within site) for tree height (m) at age 4 ½ years in the *E. grandis* trials at four sites in Victoria

Seedlot	Provenance	Koorlong A	Koorlong B	Shepparton	Werribee
11159	Mt. George, NSW	6.0 (13)	7.8 (4)	--	--
11996	Bulahdelah, NSW	6.5 (9)	7.7 (6)	10.9 (6)	5.2 (10)
15120	Lake Cathie, NSW	6.9 (3)	7.8 (2)	10.7 (10)	5.9 (6)
15632	Woondum, QLD	6.7 (7)	7.1 (10)	11.1 (1)	4.9 (12)
16435	Wedding Bells SF, NSW	6.5 (10)	7.0 (12)	10.6 (11)	6.1 (4)
16437	Wahau Trig, NSW	6.5 (11)	7.1 (11)	10.7 (8)	6.0 (5)
16439	Orara SF, NSW	5.8 (14)	6.4 (15)	--	--
16442	Bruxner Park, NSW	6.9 (4)	7.3 (9)	11.0 (5)	6.3 (2)
16454	Pine Creek SF, NSW	6.9 (5)	7.8 (3)	11.1 (1)	5.7 (7)
16447	Langley's Rd, Coffs Harbour, NSW	6.3 (12)	7.6 (8)	10.8 (7)	6.1 (3)
18277	Bellthorpe, QLD	6.7 (8)	7.6 (7)	10.7 (9)	5.7 (8)
ERA-1	Boambee, NSW	--	--	11.1 (3)	5.3 (9)
ERA-2	Plantation selects—Loxton, S.A.	7.7 (1)	8.0 (1)	--	--
18146	Coffs Harbour Seedling Seed Orchard	7.6 (2)	6.7 (14)	11.1 (3)	6.7 (1)
17803	CSO—Pretoria, SOUTH AFRICA	6.9 (6)	7.7 (5)	--	--
18229	<i>E. saligna</i> —Blackdown Tableland, QLD	4.9 (15)	6.8 (13)	10.1 (12)	5.1 (11)
Site Means:		6.5	7.4	10.7	5.9
S.E.D. (average) for provenance means		0.53	0.58	0.37	n.s.

S.E.D: standard error of the difference between two means

n.s.: indicates differences between provenance means were not significant

Table A3.3.2 Provenance means and (rankings within site) for diameter at breast height (cm) at age 4½ years in the *E. grandis* trials at four sites in Victoria

Seedlot	Provenance	Koorlong A	Koorlong B	Shepparton	Werribee
11159	Mt. George, NSW	6.3 (10)	8.5 (2)	--	--
11996	Bulahdelah, NSW	5.8 (14)	7.9 (6)	9.8 (4)	9.6 (2)
15120	Lake Cathie, NSW	7.0 (2)	8.0 (4)	9.3 (9)	8.8 (6)
15632	Woondum, QLD	6.9 (5)	7.9 (6)	10.0 (1)	6.1 (12)
16435	Wedding Bells SF, NSW	6.6 (6)	7.6 (12)	9.3 (10)	8.8 (6)
16437	Wahau Trig, NSW	6.3 (10)	7.2 (13)	9.2 (11)	9.0 (4)
16439	Orara SF, NSW	5.0 (15)	6.4 (6)	--	--
16442	Bruxner Park, NSW	6.6 (6)	7.7 (10)	9.8 (2)	9.0 (4)
16454	Pine Creek SF, NSW	6.6 (6)	7.9 (6)	9.7 (6)	7.4 (10)
16447	Langley's Rd, Coffs Harbour, NSW	5.9 (13)	7.7 (9)	9.4 (8)	8.4 (8)
18277	Bellthorpe, QLD	6.4 (9)	8.0 (4)	9.1 (12)	8.3 (9)
ERA-1	Boambee, NSW	-	-	9.5 (7)	9.2 (3)
ERA-2	Plantation selects—Loxton, S.A.	7.7 (1)	8.7 (1)	--	--
18146	Coffs Harbour Seedling Seed Orchard	7.0 (2)	6.4 (14)	9.8 (2)	9.7 (1)
17803	CSO—Pretoria, SOUTH AFRICA	7.0 (2)	8.2 (3)	--	--
18229	<i>E. saligna</i> —Blackdown Tableland, QLD	6.0 (12)	7.7 (9)	9.7 (5)	6.8 (11)
Site Means		6.4	7.7	9.5	8.3
S.E.D. (average) for provenance means		n.s.	n.s.	n.s.	0.96

S.E.D: standard error of the difference between two means

n.s.: indicates differences between provenance means were not significant

Table A3.3.3 Provenance means and (rankings within site) for conical tree volume (dm³) at age 4 ½ years in the *E. grandis* trials at four sites in Victoria.

Seedlot	Provenance	Koorlong A	Koorlong B	Shepparton	Werribee
11159	Mt. George, NSW	7.2 (11)	16.4 (6)	--	--
11996	Bulahdelah, NSW	5.7 (13)	14.8 (7)	28.1 (4)	12.6 (6)
15120	Lake Cathie, NSW	8.9 (3)	17.1 (2)	24.5 (10)	14.7 (2)
15632	Woondum, QLD	8.7 (6)	13.7 (11)	29.0 (1)	4.2 (12)
16435	Wedding Bells SF, NSW	8.1 (9)	13.5 (12)	24.2 (11)	13.0 (5)
16437	Wahau Trig, NSW	8.1 (10)	13.2 (13)	24.6 (9)	13.0 (4)
16439	Orara SF, NSW	4.3 (15)	10.8 (15)	--	--
16442	Bruxner Park, NSW	8.9 (4)	13.7 (10)	28.3 (2)	13.7 (3)
16454	Pine Creek SF, NSW	8.6 (7)	16.5 (4)	27.7 (5)	8.8 (10)
16447	Langley's Rd, Coffs Harbour, NSW	6.8 (12)	14.6 (9)	25.5 (7)	11.6 (8)
18277	Bellthorpe, QLD	8.2 (8)	16.4 (5)	23.9 (12)	10.1 (9)
ERA-1	Boambee, NSW	--	--	26.1 (6)	11.7 (7)
ERA-2	Plantation selects—Loxton, S.A.	12.4 (1)	18.8 (1)	--	--
18146	Coffs Harbour Seedling Seed Orchard	10.0 (2)	11.8 (14)	28.1 (3)	16.4 (1)
17803	CSO—Pretoria, SOUTH AFRICA	8.9 (5)	17.1 (3)	--	--
18229	<i>E. saligna</i> —Blackdown Tableland, QLD	5.7 (14)	14.8 (8)	25.4 (8)	6.7 (11)
Site Means		9.7	15.1	27.3	11.3
S.E.D. (average) for provenance means		n.s.	n.s.	2.92	2.67

S.E.D: standard error of the difference between two means

n.s.: indicates differences between provenance means were not significant

Table A3.4 Mean squares from analyses of variance for plot mean height, diameter at breast height (DBH) and volume of *E. grandis* at age 4½ years in four trials in Victoria

Site	Source of variation	d.f.	Mean squares		
			Height	DBH	Volume
Koorlong A.	Provenance	13	7.3658 **	2.050 ns	21.62 ns
	Family-within-provenance	34	1.8058 **	2.389 *	21.60 *
	Residual	122	0.9613	1.431	13.35
Koorlong B	Provenance	13	2.443 **	2.078 ns	33.32 ns
	Family-within-provenance	34	1.235 ns	1.904 ns	28.31 ns
	Residual	120	0.942	1.815	33.47
Shepparton	Provenance	11	1.7254 **	1.0791 ns	62.49 *
	Family-within-provenance	33	0.7760 ns	1.4015 *	63.35 **
	Residual	138	0.6438	0.9014	31.51
Werribee	Provenance	11	1.4627 ns	5.457 **	49.67 **
	Residual	68	0.7885	1.646	18.70

Note: trial data from the four sites included results from 6 individual parent tree seedlots of a single *E. saligna* provenance.*, **: indicates the factor (ie. source of variation) proved to have a significant effect in the analyses of variance at $p \leq 0.05$ or $p \leq 0.01$ respectivelyns: indicates the factor did not to have a significant effect ($p \leq 0.05$)

sites yet was poor at Shepparton. Similarly both the Bruxner Park and Coffs Harbour seed orchard were both amongst the best for volume at all sites except for at Koorlong B, and Woondum which showed the best growth at Shepparton was the poorest at Werribee.

Family-within-provenance variation

At Koorlong B differences between families for height, diameter and volume were not significant. In contrast, there were significant differences ($p < 0.05$) in all three growth traits between families-within-provenances at Koorlong A, and in DBH and volume at Shepparton (Table A3.4). At Koorlong A, mean family heights of *E. grandis* ranged from 5.2 to 8.2 m and mean volumes ranged from 3.3 to 13.2 dm³ (Table A3.5). At Shepparton the ranges in the family means for height and volume were 9.8 to 11.5 m and 17.0 to 33.2 dm³ respectively. The best *E. grandis* family for growth at Koorlong A came from Bellthorpe and that with the poorest was from Langleys Road near Coffs Harbour. At Shepparton, the best family was from Pine Creek and, just at Koorlong A, the poorest was from Langleys Road.

At both Shepparton and Koorlong A, the better families for volume came from a wide range of provenances. The top 10 families for volume at Shepparton represented 5 provenances, which themselves ranged from superior (Bruxner Park—ranked second for volume) to poor (Bellthorpe—ranked last for volume). At Koorlong A, the top 10 families also represented 5 provenances whose mean performance ranged from fourth (Bruxner Park) to twelfth by volume (Langleys Road).

Growth of the individual families of *E. saligna* relative to the *E. grandis* families varied markedly between sites. At Koorlong A, the six *E. saligna* families were all in the poorest 30% of families by volume. In contrast, the same families at Shepparton varied widely in growth performance from superior to poor—two were comparable to the 10 best individual *E. grandis* families for volume and one even ranked among the best four. The poorest *E. saligna* family at Shepparton however, ranked among the poorest four *E. grandis* families for volume.

At both Koorlong A and Shepparton, the variation between families-with-provenances of *E. grandis* was substantially greater than that between provenances. In a few cases variation within a single provenance even exceeded the total variation between the means of all provenances represented in the same trial. For example, at Shepparton families from the Wahau Trig provenance ranged in average volume from 17.2 to 32.3 dm³ while the range for provenance means at that site was only 23.9 to 29.0 dm³.

Heritability

Estimates of individual tree heritability for growth traits ranged from very low at 0.06 for DBH at Koorlong B to moderate at 0.21 for height at Koorlong B (Table A3.6). Out of the three trials, Koorlong A provided the largest heritabilities for all traits. The lowest heritabilities for each of the three traits were at Koorlong B—a site where no significant differences were detected between families-within-provenances. However, the standard errors on all the heritability estimates obtained were relatively high and only one of them, that for height at Koorlong A (0.21 ± 0.18), was larger than its standard error.

Table A3.5 Variation between families-within-provenances for DBH and volume at age 4 ½ years in the *E. grandis* trials at Koorlong A and at Shepparton in Victoria. (Results not presented from Koorlong B as differences in growth traits between family-within-provenances were not significant).

Seedlot	Provenance	No. of families	Height (m)		DBH (cm)		Volume (dm ³)	
			Provenance Mean	Range in family means	Provenance Mean	Range in family means	Provenance mean	Range in family means
Koorlong A Site								
16435	Wedding Bells SF, NSW	4	6.5	6.4–7.0	6.6	6.4–7.0	8.1	7.3–9.9
16437	Wahau Trig, NSW	5	6.5	5.3–7.5	6.3	5.5–7.4	8.1	6.6–10.9
16442	Bruxner Park, NSW	5	6.9	6.4–7.8	6.6	6.2–7.7	8.9	7.0–12.0
16454	Pine Creek SF, NSW	6	6.9	6.1–7.1	6.6	5.4–7.1	8.6	5.4–10.4
16447	Langley’s Rd, Coffs Harbour, NSW	6	6.3	5.2–7.1	5.9	4.4–7.0	6.8	3.3–9.7
18277	Bellthorpe, QLD	6	6.7	5.9–8.2	6.4	5.3–7.8	8.2	5.3–13.2
18229	<i>E. saligna</i> —Blackdown Tableland, QLD	6	4.9	4.5–5.8	6.0	5.7–6.5	5.7	4.3–6.5
S.E.D. (average) for family means				0.68		0.81		2.29
Ratio of family-variation to provenance-variation				6.0		2.9		2.3
Shepparton Site								
16435	Wedding Bells SF, NSW	6	10.6	10.4–10.8	9.3	9.1–9.4	24.2	23.2–25.9
16437	Wahau Trig, NSW	6	10.7	9.8–11.2	9.2	8.2–10.4	24.6	17.2–32.3
16442	Bruxner Park, NSW	6	11.0	10.2–11.5	9.8	9.3–10.3	28.3	23.7–32.0
16454	Pine Creek SF, NSW	5	11.1	10.2–11.3	9.7	9.0–10.5	27.7	22.8–33.2
16447	Langley’s Rd, Coffs Harbour, NSW	6	10.8	10.4–11.3	9.4	8.5–10.1	25.5	20.4–30.1
18277	Bellthorpe, QLD	6	10.7	9.8–11.5	9.1	8.0–9.9	23.9	17.0–28.9
18229	<i>E. saligna</i> —Blackdown Tableland, QLD	6	10.1	9.5–10.7	9.7	8.7–10.4	25.4	19.5–30.4
S.E.D. (average) for family means				n.s.		0.61		4.05
Ratio of family-variation to provenance-variation				10.5		3.6		1.9

S.E.D: standard error of the difference between two means
n.s.: indicates differences between family means were not significant

Table A3.6 Individual tree heritabilities (within provenance) for *E. grandis* at age 4 ½ years at three Victorian sites

Trait	Individual tree heritability ± s.e.		
	Koorlong A	Koorlong B	Shepparton
Height	0.21 ± 0.18	0.09 ± 0.12	0.12 ± 0.15
DBH	0.14 ± 0.14	0.07 ± 0.10	0.08 ± 0.09
Volume	0.12 ± 0.16	0.08 ± 0.13	0.11 ± 0.10

Analyses across sites—genotype by environment interactions

With combined data from Koorlong A, Koorlong B and Shepparton, both provenance and family-within-provenance differences proved significant ($p \leq 0.05$) for height, DBH and volume (Table A3.7). In contrast, environment (trial site) by provenance and environment by family-within-provenance interactions for growth (height, DBH and volume) were not significant across these three *E. grandis* trials.

Table A3.7 Mean squares from analyses of variance across sites for plot mean height, diameter at breast height (DBH) and volume of *E. grandis* at age 4½ years in two at Koorlong and one at Shepparton in Victoria.

Source of variation	d.f.	Mean squares		
		Height	DBH	Vol
Provenance	13	9.414 **	3.424 *	66.48 *
Site x provenance	22	2.007 ns	1.423 ns	33.70 ns
Family-within-provenance	32	2.969 **	4.216 **	66.39 **
Site x family-within-provenance	56	1.709 ns	2.076 ns	42.68 ns
Residual	490	1.546	1.932	37.92

Notes:

*, **: indicates the factor (*ie.* source of variation) proved to have a significant effect in the analyses of variance at $p \leq 0.05$ or $p \leq 0.01$ respectively;

ns: indicates the factor did not to have a significant effect ($p \leq 0.05$).

Many of the provenances and families-within-provenances showed consistent growth performance, relative to site averages, across the three trials. However, there were a few exceptions with several better families for growth at one or two of the sites being ranked only mediocre to poor at the other(s), and *vice versa*. For example, one family from the Pine Creek provenance was the best family by volume at Shepparton proved only mediocre at Koorlong A and was in the poorest 25% of families at Koorlong B.

Discussion

Climatic parameters, excepting rainfall, for each of the four trial sites reported are within requirements defined for *E. grandis* by Booth and Pryor (1991) (Table A3.1). However, even though irrigation has been applied at all of the sites overcoming the rainfall limitation, growth has been only mediocre to poor in these trials. At the best site, Shepparton, average height increment was only about 2.4 m per year and at the two Koorlong sites, the averages were only 1.4 and 1.6 m per year. In contrast, Arnold *et al.* (1996) reported an average mean dominant height of 18.7 m to age 5½ years (3.4 m per year) from an effluent irrigated *E. grandis* trial near Loxton, SA, where the climate is similar to that at Koorlong. Also, in another effluent irrigated trial near Wagga Wagga, NSW, the average height of

E. grandis was reported to have reached more than 9.5 m in less than three years (>3.2 m per year) (Myers 1994).

Although the growth of the *E. saligna* provenance was relatively poor, this result can not be considered indicative of that species' potential at any of the four sites involved in this research. A single natural stand provenance is not an adequate sample of this species, particularly as the variation in growth between provenances within both *E. saligna* and *E. grandis* can far exceed differences between the means of the two species (e.g. Burgess 1988).

An important factor that has likely constrained growth of the *E. grandis* at least at Koorlong, is the low to very low daytime humidities typically experienced there over much of the growing season. *E. grandis* is a sub-tropical species and under conditions of low humidity it has a tendency to close its stomata and stop carbon dioxide uptake, even when adequate soil water is present (Myers *et al.* 1996). This stomatal response can limit its growth in drier Mediterranean type environments, such as that at Koorlong, even where luxuriant irrigation is supplied. In combination with this, problems were encountered with irrigation systems during the first year after establishment at Koorlong and there were occasions at these three sites where insufficient water was being supplied to the site to keep the trees adequately hydrated. At Shepparton, irrigation problems during the first two years on some occasions temporarily limited the water supply to the trial.

Alkalinity of the Koorlong soils (pH 8.0 to 8.5) may be another factor contributing to the slower growth there, relative to that at Shepparton. Although *E. grandis* is moderately tolerant of pHs in the range 8.0–9.0, best growth is obtained with soil pH closer to 7 (Marcar and Khanna 1997). At Shepparton, which provided the best growth overall of the four sites, soil pH was closer to optimum for this species at 6.6 for surface soils and 7.5–8.3 for deeper profiles.

At each site, plantation select material from Loxton and/or the Coffs Harbour seed orchard material generally showed the best growth of all provenances. It was only at Shepparton where unimproved natural stand provenances matched the growth of improved material. The good performance by the Coffs Harbour seed orchard material at three of the trial sites was to be expected. Its volume growth has generally been similar or superior to good natural stand provenances in trials in both Australia and Sri Lanka (Davidson 1998; Cromer *et al.* 1991; Bandara *et al.* 2001).

Poor growth of the Coffs Harbour seed orchard material at Koorlong B is thought to be due to an unfortunate combination of environmental factors, as noted above. However, its inherent genetic variability may also have contributed to this result. High variability among family progeny from the Coffs Harbour Seed Orchard has been observed in provenance-family trial in Sri Lanka (Bandara *et al.* 2001). While some of the families from the Coffs Harbour Seed Orchard showed very poor mean volume in Sri Lanka (age 27 months), others were amongst the best of the 88 families represented in that trial.

The material from the plantation selects at Loxton was notable for its clear and consistent superior growth in both trials at Koorlong. It generally also shows superior form in that environment (E.B. Allender pers. comm.). Clearly the intensive phenotypic selection in the Loxton plantation at around age 4½ years proved very effective in identifying superior parent trees. The worth of intensive selection for genetic improvement of *E. grandis* had been demonstrated previously in Florida. There, four generations of intensive phenotypic selection, provided gains of more than 160% in volume and significant increases in stem straightness relative to their first generation material, all in a period of less than 20 years (Meskimen 1983; Rockwood 1991).

The better growth of material from Loxton Plantation selects compared to that of the South African seed orchard material in both Koorlong trials is not surprising. Material from early South African orchards has shown disappointing growth relative to that from better natural stand provenances in trials in both South Africa (Darrow 1983) and Florida (Rockwood and Meskimen 1991). The *E. grandis* introduced to South Africa in the late 19th century, upon which earlier plantation and

breeding programs was based, is thought to have originated from collections from northern New South Wales or southern Queensland (Burgess *et al.* 1985). In northern New South Wales one of the more commonly used seed collection areas for earlier base populations sent to other countries was Orara East (Burgess 1988). Unfortunately, some seedlots from this locality have shown inferior performance in number of trials, including ones near Coffs Harbour (Burgess 1988), and the two reported here at Koorlong. Introductions of rangewide collections of *E. grandis* to South Africa in the later part of 20th century have since provided a better genetic base for breeding programs there (CABI 1998).

The overall lack of significant interaction between genotypes (provenances and families-within-provenances) and environments (trial sites) across the Koorlong A, Koorlong B and Shepparton sites is important to both tree breeders and those involved in plantation establishment. Most provenances and also families selected for superior performance at one of these sites should, on average, perform relatively consistently across sites. Likewise material identified as mediocre or poor at one site would be expected to perform similarly elsewhere. However, this inference is limited to the range of environments represented by the three trial sites. In a substantially different environment, the expectation for relative growth performance would be uncertain. Significant interactions between *E. grandis* genotypes and environmental factors for growth traits have been reported elsewhere (Burgess 1988; Endo and Easley 1991). For example, Tuckers Knob and Bellinger River provenances (both New South Wales) have shown consistent performance among other natural stand provenances in trials across a broad range of environments in Australia, South Africa and the United States, while Orara East and Orara West provenances (both New South Wales also) have varied considerably in their relative performance across the same environments (Burgess 1988).

The variation found between families-within-provenances in the Koorlong A and Shepparton trials was to be expected. Considerable differences among families-within-provenances of *E. grandis* have been reported from trials in many countries (e.g. Reddy and Rockwood 1989; Endo and Easley 1991; Burgess *et al.* 1996). In a Sri Lankan provenance-family trial the variation in growth between families-within-provenances at age 27 months proved to exceed most of the differences between provenances (Bandara *et al.* 2001). The second best family for growth in that trial was found to come from one of the poorest provenances represented there.

Even though heritability of growth traits in the trials reported were relatively low, when combined with the differences between families-within-provenances and also that between individuals-within-families there is a good basis for significant genetic improvement in subsequent generations.

Although one of the key objectives in establishing the four *E. grandis* trials reported was to evaluate genetic variation in its susceptibility and tolerance to defoliating insect pests, it has not been possible to do this for up to about age 4½ years—the timing of assessments for this report. However, since that time there has subsequently been substantial defoliation in both Koorlong trials by larvae of autumn gum moth (*M. privata*). Genetic variation in defoliation, tolerance and growth response to those events will be reported separately.

Conclusions

Provenance selection was shown to be substantially important for optimising *E. grandis* growth in these effluent irrigated trials, with genetically improved material providing among the best growth. The substantial variation shown between families-within-provenances creates opportunities for genetic improvement in the species through selection for a subsequent generation.

Acknowledgments

We owe thanks to Lower Murray Water, Goulburn Valley Water and Melbourne Water for their significant support of the trial work. Ted Allender of Environmental Revegetation Australia Pty Ltd provided invaluable assistance in the establishment and maintenance of the trials at Koorlong and provision of two of the seedlots. The Joint Venture Agroforestry Program contributed to the financial support for the trials. John Dowse, Rex Sutherland, Michelle Court, Martin Steinbauer and Mamoru Maksuki carried out data collection to the usual high standard.

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