# Benefits of weed control and fertiliser application to young *Eucalyptus dunnii* stressed from waterlogging and insect damage

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## Summary

A trial designed to measure benefits to growth of post-establishment weed control and fertiliser (diammonium phosphate, DAP) application in a young *Eucalyptus dunnii* plantation was used to test whether young trees benefiting from such silvicultural practices were more resilient to stress from waterlogging and insect damage. Chlorophyll fluorescence (Fv/Fm) was used as the measure of tree stress. Both the weed control and fertiliser treatments had significant beneficial effects on diameter and height of surviving trees. Tree growth response was greater for weed control than fertiliser application. Neither treatment, however, appeared to alleviate the impact of flooding on tree mortality. Insect damage, in particular from the leaf blister sawfly *Phylacteophaga froggatti*, was negatively correlated with tree size, which in turn was directly influenced by the degree of soil inundation, weed control and fertiliser application. It is argued that growth results from a balance of beneficial conditions and a range of stressful factors. Post-establishment practices such as weed control and fertiliser application can improve tree resilience to stress-inducing factors that cannot be managed easily.

*Keywords:* waterlogging, stress, *Eucalyptus dunnii*, diameter, growth, weed control, fertilisers, chlorophyll, fluorescence, leaf blister sawfly, *Phylacteophaga froggatti*, insect pests

## Introduction

Plantation trees are subject to a varying range and intensity of environmental factors causing physiological stress. Although acting simultaneously on the plant, their effects may be hierarchical, some factors acting as primary stressors which considerably reduce the tree's vitality and others as secondary stressors which further lower vitality (Lichtenthaler 1996). Post-establishment silvicultural practices such as weed control and fertiliser application may alleviate the potential impact of some of these stress-inducing environmental conditions (Margolis and Brand 1990; Bolhar-Nordenkampf *et al*. 1994). Several Australian studies have demonstrated that intensive silvicultural practices during the establishment phase of eucalypt plantations promote vigorously growing trees (Turnbull *et al*. 1988; Birk and Turner 1992). We assume that vigorous healthy trees are more resilient (*sensu* Rapport *et al*. 1998) to a range of stressful factors, while less vigorous trees are likely to have a lower tolerance threshold to stressful agents such as leaf-damaging insects (Strauss and Agrawal 1999). If this is indeed the case, then plantation health can be managed through practices which aim to minimise overall tree stress rather than focusing on specific stress-inducing agents (Norris 1988; Browning 1998). Stone and Clarke (1998) advocated maximising the physiological vigour of plantation eucalypts in order to reduce the impact of herbivorous insects.

To date, most eucalypt health assessment studies have been based on subjective estimates of visual features of tree canopy condition and damage. This can lead to problems of standardisation and interpretation of canopy health (Innes 1993; Ferretti 1997; Stone 1999). Recently, several authors (e.g. Mohammed *et al*. 1995; 1997; Lichtenthaler 1996) have advocated the need to obtain quantitative physiologically based parameters that relate to tree condition and vigour, in addition to visual estimates and physical measurements, for tree health assessment. In green foliage, the largest part of light energy absorbed by the leaf pigments is used for photosynthesis. A minor part is re-emitted as heat and chlorophyll fluorescence. In stressed leaves photosynthetic activity declines and the chlorophyll fluorescence emission increases (Long *et al*. 1994). Measurement of chlorophyll fluorescence has successfully been used as a generic diagnostic tool for the detection of physiological stress in plants arising from a range of stressful environmental factors such as drought, heat, cold, air pollution and nutrient deficiency (e.g. Schreiber and Bilger 1987; Mohammed *et al*. 1995; Lichtenthaler and Miehé 1997). One chlorophyll fluorescence parameter, Fv/Fm (the ratio of maximum variable to maximum total fluorescence) is a direct quantitative measure of the efficiency of the photosynthetic apparatus and can be easily measured by portable instrumentation (Mohammed *et al*. 1995). Sustained decreases in photochemical efficiency have been shown to influence both survival and growth rates of eucalypt seedlings (Holly *et al*. 1994; Ball *et a*l. 1997; Close *et al*. 2000). Because of our interest in demonstrating a possible relationship between chlorophyll fluorescence, tree growth and visual poor health of tree crowns, a subsample of trees in this study was selected for field measurements of Fv/Fm using a portable chlorophyll fluorometer.

Trees measured in this study were planted as a *Eucalyptus dunnii* Maiden trial plantation designed to determine benefits to growth of post-establishment weed control and fertiliser application. Within three months of trial establishment, the district received above-average rainfall resulting in a flood that waterlogged the trial site to varying degrees of wetness (Fig. 1).

Waterlogging stresses plants by depriving roots of atmospheric oxygen within the rhizosphere which then reduces aerobic respiration and root metabolism (Broadford and Yang 1981; Drew 1983; Kozlowski 1984). This waterlogging coincided with the final two occasions of trial measurements (Fig. 1). Another stressful factor, that of feeding damage from insects, and in particular from the leaf blister sawfly, *Phylacteophaga froggatti* Riek (Hymenoptera: Pergidae), was also present in the plantation. *P. froggatti* populations were first detected in late 1998 and increased over the summer and autumn months of 1999.

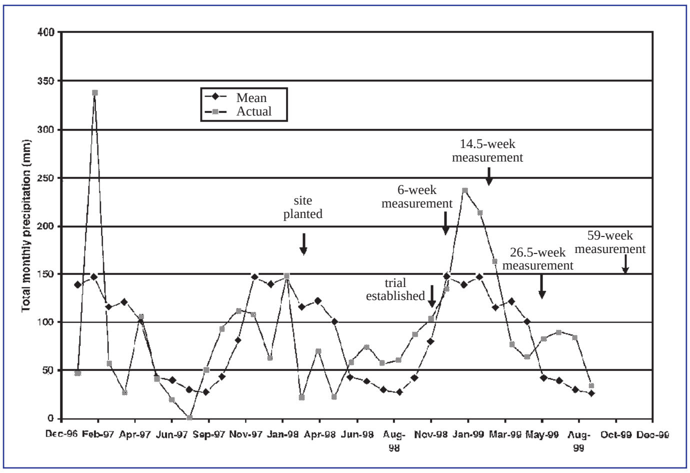


**Figure 1.** Actual and total monthly rainfall pattern over the trial period. Rainfall data were obtained from the Mallanganee weather station, 5 km NE of the trial site.

The occurrence of these insects permitted a look at the effects on tree growth of two uncontrolled environmental stresses (waterlogging and insect damage) in combination with two silvicultural treatments (weeding and fertilisation). These circumstances enabled us to test our hypothesis that silvicultural practices that promote tree vigour may assist in reducing the deleterious impact on tree growth from stressful factors that cannot be easily managed.

## Materials and methods

### Study area and experimental design

The trial site was part of a young commercial *E. dunnii* plantation located (28º58'S, 152º41'E, altitude 190 m) approximately 40 km southwest of Casino in north-eastern New South Wales. The site is on a drainage plain with soil classified as Black Vertosol derived from a mixture of basalt and sandstone geology (Grant 2001). These soils are heavy textured with high clay content and with high shrink/swell characteristics. A soil survey of the district, including four samples from the trial plantation, revealed that while soil nitrogen and phosphorus were not limiting for *E. dunnii* growth, the site could not be considered highly fertile (K. Montagu, SFNSW, *pers. comm*., unpublished data). The vegetation prior to plantation establishment was predominantly native pasture used for beef cattle grazing and remnant dry sclerophyll forest. In late 1997 the area was ripped and mounded at 4-m intervals with a 6-disc Savannah plough. Several weeks later, the mounds were sprayed with the herbicide Roundup® (3 L $ha^{-1}$ , a.i. glyphosate). Three weeks after that, the mounds were cultivated with an offset plough and simazine (5 kg a.i. $ha^{-1}$) was applied as a residual herbicide. In February 1998 *E. dunnii* stock seedlings, approximately 30 cm in height, were planted at a spacing of 3 m along the mounds with a machine planter and fertilised with 50 g granular diammonium phosphate (DAP) buried alongside each seedling. The seedlings were considered to have been in good condition during the early establishment phase of the plantation (P. Brennan, SFNSW, *pers. comm.*)

The trial was installed on the site 8 months after planting (1 October 1998) (Fig. 1). Because of a slight variation in tree spacings along some of the rows at the trial site, the treatments were initially applied within an underlying randomised block design. An initial linear mixed-model analysis revealed that the block effect was negligible. Subsequent analyses therefore treated the trial design as completely randomised. The treatments were applied as a two-way factorial consisting of weed control (present or absent) and fertiliser application (none, 50 g or 150 g of granular DAP) as the main effects, with 4 replicates of each treatment (24 treatment plots in total) (Fig. 2). Each treatment plot consisted of 6 rows x 10 trees although the actual number of trees per block varied due to mortality (6% average across the site) during the previous 8 months. A single-row untreated buffer strip was provided around each replicate plot.

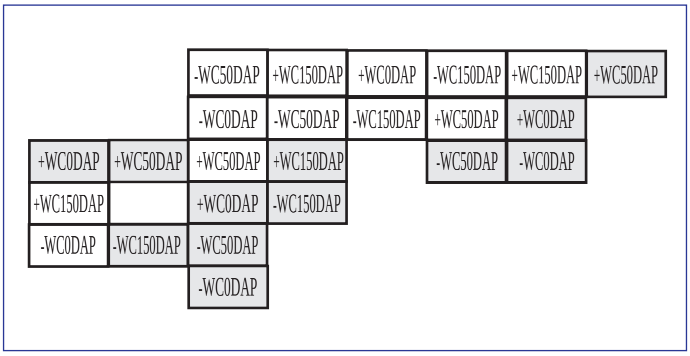


**Figure 2.** Experimental layout of the treatment blocks in the young *Eucalyptus dunnii* plantation ( +WC and –WC = presence and absence of weed control; 0DAP, 50DAP and 150DAP = none, 50 g or 150 g of granular diammonium phosphate). Those treatment plots with a mean soil wetness score/tree of greater than 2 were categorised as being 'wet' during April 1999 and are shaded grey. Treatment plots with a mean soil wetness score/tree of less than 2 were categorised as being relatively 'dry' and are unshaded.

Weed control was achieved by spraying Roundup® (360 g glyphosate $L^{-1}$) and a red vegetable dye with a backpack and wand in a one meter radius around the base of each tree. The herbicide was applied under still conditions and no accidental spray drift onto tree foliage was observed. DAP granules were placed in slits 10 cm deep and located 30 cm from the base of each tree. Mean tree height at the time of trial establishment was 1.6 m ± 0.32 (mean± SE).

### Tree measurements

Tree stem diameters were initially measured at 30 cm above ground when the treatments were applied. Tree heights were measured five times; at trial establishment (8 months after planting), 6 weeks, 14.5 weeks, 26.5 weeks and 59 weeks after treatment application, while tree diameters over bark at 1.3 m were measured four times: at 6 weeks, 14.5 weeks, 26.5 weeks and 59 weeks after treatment application (Fig. 1). At 1.3 m height, these diameter measurements were well above the flood water level where stem hypertrophy may have occurred in response to waterlogging (Blake and Reid 1981).

At the assessment at 26.5 weeks (5-7 April 1999), the incidence and severity of insect damage to tree canopies and the leaf chlorophyll fluorescence were measured. Incidence refers to the proportion of total crown foliage that was damaged while severity refers to the extent of damage on each leaf. For the incidence of insect damage, ten representative trees, in an approximate left to right diagonal across each treatment replicate, were visually scored over the entire canopy to the nearest 10%. The severity of attack (i.e. the average area affected per leaf amongst those leaves included in the incidence estimate), was scored into one of the following categories: 1=0-3%; 2=3-6%; 3=6-12%; 4=12-25%; 5=25-50%; 6=50-75%; 7=75-95%; 8=>95%. There were two leaf age classes present on the canopies - a class of leaves initiated during the previous spring and early summer and fully mature at the time of assessment, and a much smaller proportion (ranging from 0% to about 10%) of younger expanding leaves (autumn flush). The two leaf age classes were assessed separately. Only the incidence and severity damage scores for mature foliage were used in this analysis because the most abundant type of damage was that caused by the leaf blister sawfly (*P. froggatti*) and this was restricted to mature foliage.

Measurements of the chlorophyll fluorescence parameter, Fv/Fm, were obtained from 20 randomly-selected mature leaves per crown from two trees representative of the ten trees assessed for insect damage, using a portable chlorophyll fluorometer (Fluorescence Induction Monitor; Fim 1500; ADC, Hertshire, UK) during the mid-morning hours of 5-7 April 1999. A single leaf clip was placed on each leaf for 15 minutes dark adaptation before recording the Fv/Fm values. While insects may have damaged many of the twenty leaves selected per tree, the clips were placed on non-necrotic leaf tissue only. The weather conditions at the time of the fluorescence measurements were similar on all three days, clear and mild (range 17ºC to 22ºC).

Knowledge of the pre- and post-treatment nutrient status of foliage in this trial would have been very desirable, but unfortunately leaf nutrient analysis was not undertaken.

### Soil moisture conditions

Soil moisture conditions were good at the time of planting, and precipitation in the following winter close to average (April – July 1998; Fig. 1). During the first three months of 1999, however, rainfall was above average. The local plantation officer (P. Shoebridge, SFNSW, Casino Region) observed that by March 1999, water was draining from the surrounding hills onto the plain causing surface water to appear within the plantation and trial site. By the 26.5 week measurement (5 April 1999) rainfall was below average but surface water was still present to a varying degree within the plantation. A simple index reflecting the degree of waterlogging around each tree was devised in the absence of instrumentation or resources for gravimetric determination of soil moisture content. This involved a visual estimate of surface soil wetness around the base of every tree in the trial during the 26.5- and 59-week tree measurements (5 April 1999 and 20 October 1999). Soil wetness was scored into one of four categories: 1 = surface soil around base of tree dry; 2 = surface soil around base of the tree damp but firm to tread on; 3 = surface soil around base of tree wet and soft to tread on; and 4 = surface water present around base of tree.

### Statistical analysis

All analyses were done using the using SAS System for Windows Version 6.12 (SAS Institute Incorporated 1996, Cary, NC, USA). Tree growth response over time to the weed control and fertiliser treatments was tested by linear mixed model analysis using the MIXED procedure in which initial stem diameter and the soil wetness score were treated as covariates (SAS Institute Inc. 1992). Both the repeated measures of actual tree heights and diameters were analysed by this procedure. This procedure fits linear models with both fixed and random effects and does not rely on the assumption that all observations are independent. Treatments were compared using least-squares means derived from the mixed-model analysis. Comparisons of means on non-parametric data were tested using the NPAR1WAY procedure while correlations were examined by computing Spearman correlation coefficients (SAS Institute Inc. 1987).

## Results

### Plantation flooding

The soil wetness scores assessed at the base of all trees in April 1999 were used to compare the spatial distribution of the relatively dry areas compared to the relatively wet areas with respect to the treatments. Those treatment replicates with a mean soil wetness category score of 2 or greater were classed as ‘wet’ while those with a mean category score less than 2 were classed as ‘dry’ (Fig. 2). Half the replicates were classed as being relatively wet, and all six treatments had at least one replicate in this category. Overall the soil wetness category score was not significantly different between treatments (Kruskal-Wallis test, $\chi^2$ = 6.63, d.f. = 5, $P$ = 0.250). Overall, both stem diameter and tree height increments were highly negatively correlated with the soil wetness scores obtained during the 26.5- and 59-week measurements (Fig. 1, $P$ = 0.0001 for each Spearman rank correlation coefficient). During the period between these two measurements overall mean wetness category score decreased from 2.66 $\pm$ 0.04 to 1.81 $\pm$ 0.02 ( $\pm$SE).

### Growth response to treatments

Both the two model covariates, initial tree diameter (obtained at tree age 8 months) and the soil wetness score (obtained in April 1999), significantly influenced tree height and diameter (Tables 1 and 2). After adjusting for the effects of the two covariates, the analysis indicated that both weed control and DAP had a significant effect on tree diameter over the four measurement periods (Table 1). The effect of weed control was more significant than that of DAP application on stem diameter ($P$ = 0.0002 and $P$ = 0.0199, respectively; Table 1). Tree height was also significantly influenced by weed control and application of DAP fertiliser, but the response was not as marked as it was for diameter (Table 2). Once again, the effect of weed control was more significant than that of the DAP application ($P$ = 0.0142 and $P$ = 0.0651, respectively; Table 2). The highly significant interactions with the repeated measures term (Tables 1 and 2) resulted from a nonlinear growth response over time, the larger trees growing faster than the smaller trees.

**Table 1.** Linear mixed-model analysis of tree diameter response over time after post-establishment weed control and fertiliser application to a young *Eucalyptus dunnii* plantation. Tree diameters were measured at 0.3 m when the treatments were applied, and subsequently at 1.3 m four times: 6, 14.5, 26.5 and 59 weeks later.

| Fixed terms | Numerator d.f. | Denominator . d.f. | F value (Type III) | *P* |
|---|---|---|---|---|
| Soil wetness score (tree covariate) | 1 | 3516 | 132.8 | 0.0001 |
| Initial diameter (tree covariate) | 1 | 3516 | 1734.7 | 0.0001 |
| Weed control | 1 | 14 | 24.8 | 0.0002 |
| Fertiliser | 2 | 14 | 5.25 | 0.0199 |
| Weed control x fertiliser | 2 | 14 | 1.21 | 0.3266 |
| Repeated measures of tree diameter ( 4 times) | 3 | 51 | 436.1 | 0.0001 |
| Weed control x repeated measures | 3 | 51 | 10.19 | 0.0001 |
| Fertiliser x repeated measures | 6 | 51 | 3.21 | 0.0095 |
| Weed control x fertiliser x repeated measures | 6 | 51 | 0.46 | 0.8367 |
| **Random terms** | | | **Covariance component estimates** | |
| Block x weed control x fertiliser | | | 0.1454 | |
| Block x weed control x fertiliser x repeated measures | | | 0.0694 | |
| Block x weed control x fertiliser x tree | | | 0.3082 | |
| Residual | | | 0.2311 | |

**Table 2.** Linear mixed-model analysis of tree height response over time after post-establishment weed control and fertiliser application to a young *Eucalyptus dunnii* plantation. Tree heights were measured five times, initially when the treatments were applied and then 6, 14.5, 26.5 and 59 weeks later.

| Fixed terms | Numerator d.f | Denominator . d.f( | F value Type III) | *P* |
|---|---|---|---|---|
| Soil wetness score (tree covariate) | 1 | 4725 | 61.06 | 0.0001 |
| Initial diameter (tree covariate) | 1 | 4725 | 900.99 | 0.0001 |
| Weed control | 1 | 17 | 7.46 | 0.0142 |
| Fertilizer | 2 | 17 | 3.22 | 0.0651 |
| Weed control x fertiliser | 2 | 17 | 1.51 | 0.2484 |
| Repeated measures of tree diameter ( 4 times) | 3 | 68 | 679.59 | 0.0001 |
| Weed control x repeated measures | 3 | 68 | 2.70 | 0.0375 |
| Fertiliser x repeated measures | 6 | 68 | 1.69 | 01163 |
| Weed control x fertiliser x repeated measures | 6 | 68 | 0.93 | 0.4976 |
| **Random terms** | | | **Covariance component estimates** | |
| Block x weed control x fertiliser | | | 0.00421 | |
| Block x weed control x fertiliser x repeated measures | | | 0.0313 | |
| Block x weed control x fertiliser x tree | | | 0.0925 | |
| Residual | | | 0.3097 | |

The treatment means for tree diameter (lsmeans with 95% confidence intervals) presented in Figure 3 show that responses to all three weed control treatments (+WC0DAP, +WC50DAP, +WC150DAP) were significantly greater than those to the no weed control and 0DAP and 50DAP treatments, but not so when 150DAP was applied (-WC150DAP). While there appears to be no significant benefit of fertiliser application within the weed control treatments, the application of 150 DAP in the absence of weed control produced a significant improvement in tree diameter. Mean tree heights in all three weed control treatments were significantly greater than in the absence of both weed control and fertiliser application, but not when either 50 or 150 g DAP/tree was applied (Fig. 3). Both stem diameter and tree height increments were highly negatively correlated with the soil wetness scores obtained during the 26.5- and 59-week measurements ($P$ = 0.0001 for each Spearman rank correlation coefficient).

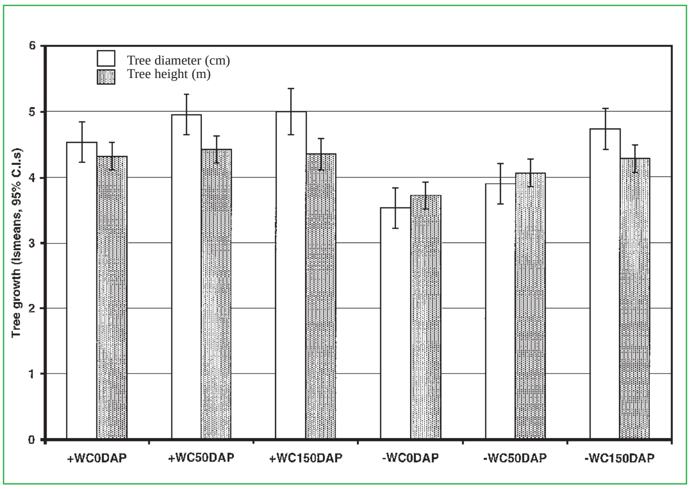


**Figure 3.** A comparison between treatments (+WC and –WC = presence and absence of weed control; 0DAP, 50DAP and 150DAP = none, 50 g or 150 g of granular diammonium phosphate) of mean stem diameter increments (DBH at 1.3 m, cm) (11 November 1998 – 20 October 1999) and tree height increments (m) (1 October 1998 – 20 October 1999) of *Eucalyptus dunnii* planted in February 1998 and treated in October 1998. Means are least-squares means derived from the linear mixed model; vertical bars = 95% confidence levels

Tree mortality (percent dead trees per plot) was significantly correlated with the mean soil wetness scores and this relationship strengthened over time (comparing Spearman rank correlation coefficients, $P$ increased from 0.05 to 0.01, n=24). In contrast with tree growth responses, there was no significant effect of weed control or DAP on tree mortality. For example, mean percent mortality was not significantly different between treatments at the 26.5 week measurement (Fig. 1, Kruskal-Wallis test, $\chi^2$ = 5.02, d.f. = 5, $P$ = 0.41). Mean tree mortality per treatment rose to 18.0% ± 2.4% (± SE) by the 14.5 week measurement, by which time the plantation had become waterlogged, and increased to 23% ± 2.6% by the 59-week measurement.

## Tree growth increment and chlorophyll fluorescence

It was observed that many of the *E. dunnii* canopies standing in waterlogged soil had purplish red foliage, both mature and immature leaf classes being discoloured. If a tree selected for chlorophyll fluorescence measurements possessed this type of foliage, purplish red mature leaves were included in the assessment, although measurements were not taken directly from necrotic tissue damaged by insects.

There were several significant correlations between tree growth, soil wetness, tree stress as measured chlorophyll fluorescence (mean canopy Fv/Fm) and insect damage during the period of above-average rainfall (during the period of inundation of the plantation) (Table 3). Chlorophyll fluorescence measurements were significantly negatively correlated with the soil wetness score. Both tree diameter and height increment were negatively correlated to the soil wetness score and positively correlated to tree stress as measured by Fv/Fm. These two relationships appear to be stronger for tree height increment than tree diameter increment.

## Tree growth increment and insect damage

The dominant foliage-damaging insect present in the young *E. dunnii* plantation during the 1998/99 summer was *Phylacteophaga froggatti*. *P. froggatti* larvae form irregular

**Table 3.** Correlation matrix based on Spearman rank-correlation coefficients between tree height and diameter increments (13 January 1999-5 April 1999), and soil wetness score, mean tree stress (chlorophyll fluorescence) and canopy insect damage (both assessed 5 April 1999) across the two-way factorial treatments of weed control and fertiliser application

| | Diameter increment | Height increment | Soil wetness score | Chlorophyll fluorescence (mean Fv/Fm) | Incidence of insect damage |
|---|---|---|---|---|---|
| Height increment | 0.70*** | | | | |
| Soil wetness score | -0.50*** | -0.65*** | | | |
| Chlorophyll fluorescence (mean Fv/Fm) | 0.55*** | 0.60*** | -0.58*** | | |
| Incidence of insect damage | -0.43** | -0.41** | 0.10 ns | -0.20 ns | |
| Severity of insect damage | -0.51*** | -0.31* | 0.30* | -0.24 ns | 0.58*** |

*$P < 0.05$; **$P < 0.01$; *** $P < 0.001$; ns not significant; n = 48

brown blisters on the upper surface of mature leaves. High infestation levels were also observed in other *E. dunnii* plantations throughout the district. Leaf chewing damage by chrysomelid species (Coleoptera) and tip-feeding by *Amorbus* species (Coreidae: Hemiptera) were also present but at a much lower incidence.

Both the levels of mean incidence and severity of insect damage were significantly different between the six silvicultural treatments (Kruskal-Wallis test, for incidence, $\chi^2 = 20.4$, d.f.=5, $P = 0.001$, n = 240 trees; for severity, $\chi^2 = 27.9$, d.f. = 5, $P = 0.0001$, n = 240 trees). In both cases, the significant difference arose not from fertiliser application but from the presence or absence of weed control. The mean incidence of damage for the three treatments with weed control was 78% ± 3.2 (mean ± SE, n=120 trees) while for three treatments without weed control it was 96% ± 3.2 (n=120 trees). Similarly, for severity of attack the scores were 7.3 ± 0.20 versus 8.8 ± 0.24.

When tree growth was examined after pooling all trees, both diameter and height increments were negatively correlated to both incidence and severity of insect damage (Table 3). Thus there was more leaf blister sawfly damage on the smaller, slower growing trees. Trees that were more stressed according to the chlorophyll fluorescence readings also had higher levels of insect damage but the correlation was not significant. The severity of insect damage (e.g. relative density of sawfly larval mines per leaf) was significantly correlated to the soil wetness score, whereas the incidence of damage was not significantly correlated.

## Discussion

### Tree growth response

The initial objective of this trial was to assess the potential benefits of post-establishment weed control and nutrient addition (as DAP) on early growth rates, and on levels of foliar damage due to insect attack. Inundation of the young *E. dunnii* plantation during the second summer after planting (about three months after weed control and fertiliser treatments were carried out) added a major uncontrolled factor to the trial. This event provided an opportunity to examine the cumulative direct effects of, and interactions between, several stresses (controlled and uncontrolled) on tree growth.

The underlying reasons for the observed spatial variation in relative extent of soil waterlogging (e.g. possible variations in slope or subsoil density affecting local drainage) were not investigated. However, our assumption that the effect of the resulting waterlogging was a significant stressful factor on young *E. dunnii* growth was confirmed in our results (Tables 1, 2 and 3). Waterlogging beyond a certain point stresses plants by depriving roots of atmospheric oxygen within the rhizosphere (Kozlowski 1984), and in the absence of oxygen roots die and decay (Drew 1983). This anaerobiosis can also lead to an increase in leaf abscission, especially of older leaves (Ladiges and Kelso 1977). These factors reduce growth rates and could explain the significant mortality and reduction in growth rates observed in response to waterlogging in this trial.

Under the prevailing conditions (Fig. 2) neither treatments of weed competition and fertiliser application (diammonium phosphate) alleviated the impact of flooding on tree mortality but they did partially offset the effect of flooding on the growth rates of surviving trees. Trees with both weed control and fertiliser application tended to be significantly larger than trees without such treatments. Tree growth response was greater for weed control than fertiliser application. Response to the fertiliser application was less distinct and in absence of appropriate nutrient analyses of the soil and foliage, the results are difficult to interpret, especially with respect to the influence of waterlogging. Leaching of N may have resulted from the waterlogging. Alternatively the anaerobic soil conditions may have directly interfered with P uptake or induced Mn toxicity (Atwell *et al*. 1999). Other studies have demonstrated that the benefits of fertilisation under waterlogging conditions can vary depending on the plant species and local environmental conditions. For example, young wheat plants raised under conditions that encouraged a high nitrogen status before an anaerobic treatment to the roots were shown to be less susceptible to injury and growth inhibition than nutrient-impoverished plants (Trought and Drew 1981). Hook *et al*. (1983) demonstrated experimentally that under anaerobiosis, the application of phosphorus improved the growth of potted loblolly seedlings but not swamp tupelo seedlings. A comparison of Tables 1 and 2 also reveals that stem diameter growth appeared more responsive to the two silvicultural treatments compared to tree height. This probably reflects the greater sensitivity of tree height to overall site quality.

### Detection of stress in young *E. dunnii*

While eucalypts are well adapted to cope with diurnal fluctuations in temperature and light intensity, especially in their natural locations, through mechanisms such as regulated photoinhibition (Ögren and Evan 1992), many environmental stresses may permanently damage this function. Detailed insight into the photosynthetic functioning requires repeated diurnal and seasonal measures of Fv/Fm and other chlorophyll fluorescence parameters in order to differentiate between permanent damage and temporary reduction in photochemical efficiency (Long *et al*. 1994; Mohammed *et al*. 1995). However, the approach taken in this study may be suitable for obtaining a rapid quantitative measure of relative tree stress in young eucalypts.

The purplish red foliar colouration of many of the *E. dunnii* trees located in neighbouring low-lying areas or in the 'wet' areas within the trial site were the visual symptoms of these stressed trees. Anthocyanins are responsible for the red to purple colouration of eucalypt leaves (Sharma and Crowden 1974). While this discolouration has been observed for other species of eucalypts subjected to waterlogging (Ladiges and Kelso 1997), both P deficiency and Mn toxicity are known to enhance anthocyanin production (Atwell *et al*. 1999). Close *et al*. (2000) demonstrated a relationship between seedling growth response, cold-induced reduction of photochemical efficiency as measured by Fv/Fm, and concentration of anthocyanin pigments in seedling *E. nitens* (Deanne & Maiden) Maiden and *E. globulus* Labill. The production of anthocyanin pigments may, therefore, be a generic physiological response of many eucalypt species to impairment of the photosynthetic apparatus caused from a wide range of environmental factors.

**Leaf blister sawfly**

In addition to observing the purple discolouration of foliage associated with waterlogging, we also assessed the level of brown necrosis caused by the leaf blister sawfly larvae (*P. froggatti*) on a subsample of trees. Many studies have demonstrated increased levels of insect herbivore on plants growing under stressful conditions (e.g. Larsson and Tenow 1984; White 1984; Hix *et al*. 1987; Stone and Bacon 1994; Cobb *et al*. 1997), although there is still much debate in the literature associated with the outcomes of plant stress and insect herbivore (e.g. Larsson 1989; Waring and Cobb 1989; Jones and Coleman 1991; Price 1991; Koricheva *et al*. 1998). Silvicultural treatments intended to alleviate host tree stress and improve tree vigour may also directly influence herbivorous insect populations either positively or negatively. A positive influence may be generated, for example, through an improvement in food quality following N fertilisation, or through loss of habitat preferred by the enemy complex following weed control (Nowak and Berisford 2000; Sun *et al*. 2000).

In this study, however, while tree stress (mean canopy Fv/Fm) was not strongly correlated overall with insect damage on the canopy, there was an indirect relationship between the slower growing trees and level of insect damage. Overall the relationships studied indicated a complex set of interactions between site factors restricting growth, insect damage and physiological stress levels. Insect damage from the leaf blister sawfly *P. froggatti*, in particular, was negatively correlated with tree size; smaller trees had higher levels of insect damage. That is, the proportion of tree crown damaged from leaf-blister sawfly larvae was greater on the smaller trees. It is also the case that trees standing in waterlogged soil were smaller- though weed control on the trial site, and to a lesser degree fertiliser application, significantly improved tree growth. In this study we did not determine whether the silvicultural treatments directly altered the physiological / nutritional suitability or resistance of the host plant or produced changes to the microclimatic conditions close to the tree canopies (White 1984; Larsson 1989; Jones and Coleman 1991; Price 1991). For example, the weeds might change the microclimatic conditions restricting air movement through the canopy (Altieri 1988). *Phylacteophaga froggatti* may have a preference for sheltered conditions and hence attain higher population levels on trees surrounded by weeds (Thumlert and Austin 1994; M. Pisasale, Murray Irrigation Ltd, Wakool, NSW, unpublished data). While we were unable to separate the individual growth and stress responses to explain the underlying mechanisms linking these multi-trophic relationships, the results do show that canopy damage from *P. froggatti* was greater on the smaller trees than on the larger, less stressed trees.

**Plantation stress management**

In this trial the young *E. dunnii* were subjected to several sources of variable stresses including waterlogging, nutrient deficiency and insect attack. Flooding and insect attack were unpredicted and uncontrolled. However, the stressful factors arising from competition from weeds and nutrient deficiencies can be managed. The alleviation of one stress may reduce the potential impact of other stresses on plantation performance. Others (Norris 1988; Browning 1998) have advocated the concept of managing plantation health through tree stress management. Rather than focusing on a single specific stress (e.g. insect herbivory or moisture stress), plantation management requires a holistic multi-disciplinary approach (Stone and Clarke 1998).

The heavy-textured, poor draining soil at the study site is relatively common for many of the ex-pasture sites available for eucalypt plantation establishment in the Casino region (Grant 2001), and appears to be quite different from soils characteristic of sites where *E. dunnii* occurs naturally (Boland *et al*. 1984). This may have been the major pre-disposing stressful factor contributing to the high incidence of tree mortality after inundation. Intensive site preparation, such as mounding and adding drainage lines, can improve soil drainage, structure and aeration (Shepard 1986). This study also demonstrated that post-establishment silvicultural practices such as weed control and fertiliser application may assist in reducing stresses arising from sub-optimal site selection.

In many regions of Australia, eucalypt plantations are being established on sites that have little or no tree performance data for the species being planted. Several species trials are planned for establishment in the Casino region, including non-eucalypt taxa, in spring 2001. Ideally, extensive taxon trialling should be carried out at least 5 years prior to widespread plantation establishment in a region with no prior data on taxon performance. In practice, this opportunity does not exist and 'best guess' species/site matching has to take place. Applying intensive management practices known to promote tree vigour could reduce the risk of plantation failure or poor growth. Once knowledge of the site characteristics and associated tree growth are obtained these practices can be tailored to improve cost efficiency.

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