Assessing the impact of leaf beetles in eucalypt plantations and exploring options for their management

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Abstract

The Eucalyptus *leaf beetle* Chrysophtharta bimaculata *(Olivier) is a serious pest of the rapidly expanding eucalypt plantation estate in Tasmania. This paper reports briefly on a series of trials being carried out by Forestry Tasmania to investigate the impact of the leaf beetles and the potential for using environmentally friendly methods to reduce defoliation to below the level that will cause economic damage.*

Insect attack has reduced the wood volume of Eucalyptus regnans *plantation trees by almost 30% after eight years, and defoliation of over 50% of the new season's growth from three-year-old* E. nitens *trees has significantly affected their growth for two years. Although the beetles preferentially attack* E. regnans *trees, larval performance and survival is better on* E. nitens *foliage; thus, 1.5 times more* E. nitens *foliage is eaten by the higher number of survivors. Interplanting of tree species preferred by* C. bimaculata *in* E. nitens *plantations has shown that these trees may be useful as an early warning system for monitoring leaf beetle populations, and they may also attract beetles away from the* E. nitens *crop tree. A bioinsecticide based on* Bacillus thuringiensis *var.* tenebrionis *(Btt) (Novodor 2%), aerially sprayed undiluted at 6 l/ha, killed about 50% of young larvae within four days, and 90% died without completing their development. However, at low population levels, Novodor caused the same level of mortality over four days as natural predation in the field; further trials will test whether Novodor will reduce higher populations to a level that can be controlled by natural enemies. The Bt-based bioinsecticide shows some potential for incorporation into an integrated pest management system for managing leaf beetles because it is compatible with other biological and silvicultural control measures and does not affect most other animals, including the natural enemies, in plantations.*

Introduction

Eucalyptus plantations are becoming increasingly important in the forestry industry worldwide, with over 6 000 000 ha of eucalypt forests now growing outside Australia (Eldridge *et al.* 1994). Tasmania has over one-third of the total hardwood plantations in Australia, with an estimated 68 000 ha of eucalypts in 1997 and at least an additional 8 000 ha planted annually (Stafford and Neilson 1994). *Eucalyptus regnans* has been widely used in older plantations but *E. nitens* is now the preferred species, with about 62 000 ha in plantations in 1997.

The *Eucalyptus* leaf beetle, *Chrysophtharta bimaculata* (Olivier) (Coleoptera: Chrysomelidae), is a serious pest of eucalypt plantations in Tasmania. It occurs naturally in Victoria and Tasmania on many eucalypt species, including *E. regnans*, *E. obliqua*, *E. delegatensis*, *E. dalrympleana*, *E. nitens* and *E. globulus*, but appears to have definite host preferences (Kile 1974; de Little and Madden 1975). Both adult and larval leaf beetles (Photos 1, 2) feed on the new season's foliage, and may consume all the new growth twice during one season. Natural parasitoids and predators keep numbers of *C. bimaculata* at acceptable levels much of the time (de Little 1982; de Little *et al.* 1990). However, outbreaks occur frequently in Tasmania,

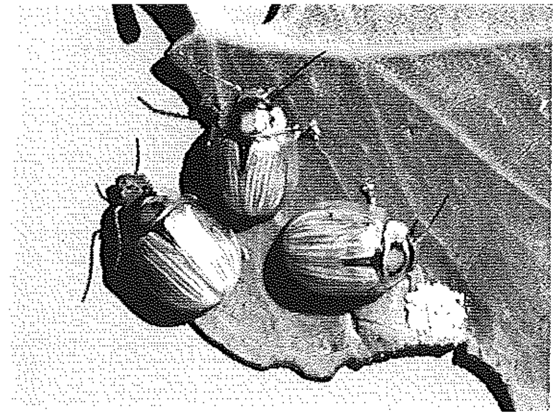

Photo 1. Adults of the eucalypt leaf beetle, Chrysophtharta bimaculata.

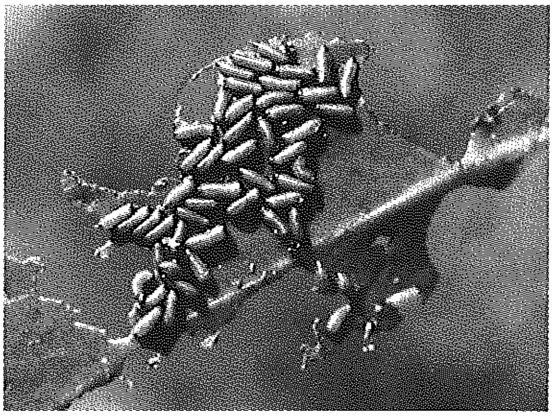

Photo 2. Larvae of C. bimaculata. *Larvae and adults may consume all the new season's foliage on young trees.*

causing considerable damage to native forests and plantations (de Little 1989).

Forestry Tasmania uses an Integrated Pest Management (IPM) strategy to control leaf beetle outbreaks and limit defoliation of plantation trees (Elliott *et al.* 1992). All young plantations are monitored regularly during the summer to assess numbers of leaves occupied by leaf beetle eggs and larvae. If the number of occupied leaves per shoot exceeds a pre-determined threshold, the plantation is further assessed and an appropriate management strategy is devised. If a reduction in the leaf beetle population is required, the plantation is sprayed with a broad-spectrum pyrethroid insecticide (cypermethrin). This effectively controls leaf beetle adults and larvae but has the disadvantage that it also kills other insect fauna in the plantation, including the natural predators and parasitoids of C. *bimaculata* (Greener and Candy 1994). An alternative insecticide being tested is Novodor® (Abbott Laboratories). Its active ingredient is an insecticidal protein derived from the bacterium *Bacillus thuringiensis* var. *tenebrionis* (Btt); the insecticidal protein crystal damages the cells lining the gut of the insect and therefore is only toxic after it is eaten. It acts specifically against some beetles and is effective against young larvae of the *Eucalyptus* leaf beetle (Elliott *et al.* 1992). It is much more environmentally friendly than cypermethrin because it does not kill the main natural predators of C. *bimaculata* (Greener and Candy 1994, 1995; N. Beveridge and J. Elek, unpublished data) or most other insects in the plantation and does not affect several major taxa of freshwater invertebrates (Davies 1994), most soil fauna (Addison 1993) or mammals.

In this research programme, the impact of defoliation by leaf beetles on tree growth is being assessed to determine the level of populations that cause economic injury; this information will enable the current monitoring protocol used in the IPM system to be refined. Alternative, more environmentally friendly methods of managing leaf beetle populations are also being investigated. This paper reports briefly on a series of trials, some of which have yet to be completed, that describe progress in both these aspects of the research.

A. IMPACT OF LEAF BEETLES ON TREE GROWTH

Methods

1. Insect exclusion trials

An insect exclusion trial to assess the impact of insect populations on tree growth was established in 1988 in the south of Tasmania (Florentine Valley: 146°28'E, 42°39'S) (Elliott *et al.* 1993). Two plots in an *E. regnans* plantation have been protected continuously from insect attack for seven years using broad-spectrum insecticidal sprays or systemic stem injections. The growth of these protected trees has been assessed regularly and compared with that of a similar number of unprotected trees in the same plantation. The leaf beetle populations in the plantations were monitored each summer until 1994/95. A similar exclusion trial was established in 1997 in young *E. nitens* plantations in northern Tasmania. It will be protected and monitored regularly to estimate the impact of insect attack on this eucalypt species.

2. *Artificial defoliation trials*

Artificial defoliation trials allow quantification of the effects of different levels of defoliation on tree growth. Three-year-old *E. nitens* trees in the Southern Forests (Arve Valley: 146°50'E, 43°10'S) that were the same size were manually defoliated at three levels of severity in one season: light (loss of 50% of the current season's growth), heavy (100%), and heavy followed by disbudding of the new shoots. The growth of these trees has been recorded for one and two years after defoliation and compared with that of undefoliated trees.

A second artificial defoliation trial just completed will compare the effects on tree growth of light or heavy defoliation and disbudding occurring early or late in the growing season, and the effects of defoliation occurring for two consecutive seasons.

3. *Quantification of leaf beetle feeding and its effect on tree growth*

Laboratory trials have compared the feeding rates of larval and adult leaf beetles on *E. nitens* and *E. regnans* (Photo 3). The mortality, development rate and efficiency of biomass conversion were also compared for the immature stages (S. Baker, J. Elek and S. Candy, unpublished data).

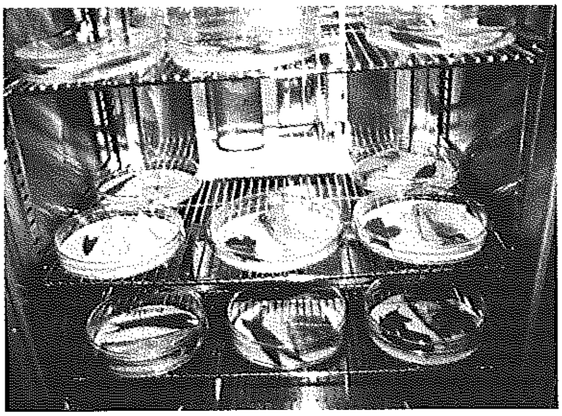

Photo 3. Laboratory trials to assess the amount of leaf tissue eaten by larval leaf beetles.

4. *Determining economic threshold of leaf beetle defoliation*

The method used for monitoring plantations for egg and larval populations in the IPM Program is being further refined as more is learnt about the aggregation behaviour of the beetle population (Clarke *et al.* 1997) and the effects of defoliation by adults and larvae on tree growth. The relationship between larval leaf beetle populations and levels of defoliation has been established for *E. regnans* (Elliott *et al.* 1992), but further work is in progress to establish this relationship for *E. nitens*.

All these results will be incorporated into a model to predict the effect of different population levels of beetles on tree growth. From this, it will be possible to assess the beetle population levels which cause growth losses that are economically significant (the economic injury level), and therefore require control measures.

Results and discussion

1. *Insect exclusion trials*

The growth of the protected *E. regnans* trees has been significantly greater than that of the unprotected trees throughout the period of protection. After eight years, mean diameter at breast height (DBH) was 53% greater for protected trees (16.00 ± 0.34 cm) than for unprotected trees (10.49 ± 0.29 cm) (Figure 1), and mean height of the five dominant trees was 25% greater for protected trees (15.93 ± 0.40 m)

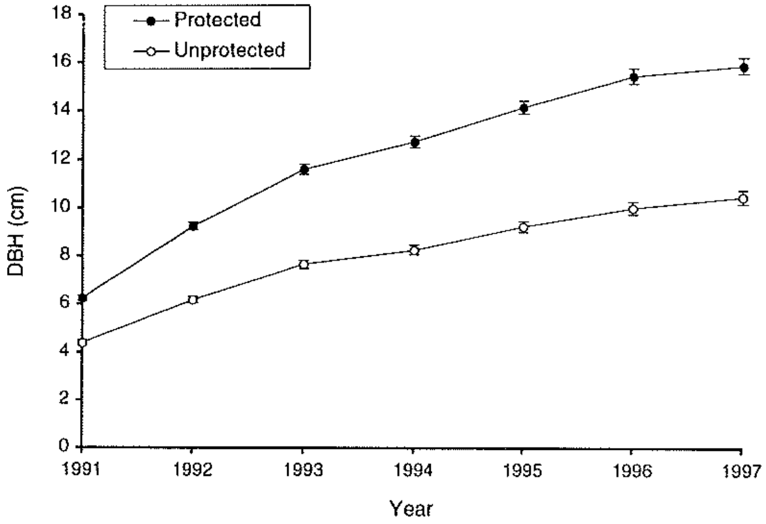

Figure 1. Comparison of diameter at breast height over bark (DBH) of all the trees in the insect exclusion trial in an E. regnans *plantation where some trees were completely protected from insect attack for eight years using broad-spectrum insecticides and some received no protection.*

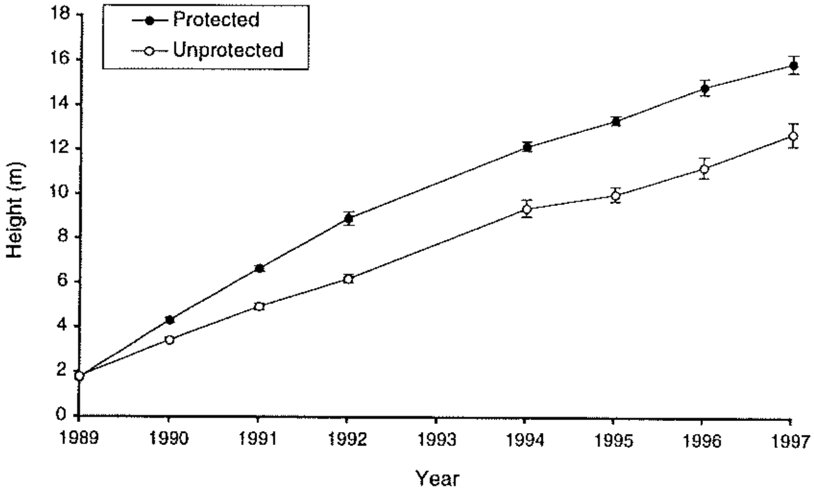

Figure 2. Comparison of height of the dominant trees in an E. regnans *plantation, where some trees were completely protected from insect attack for eight years using broad-spectrum insecticides and some received no protection.*

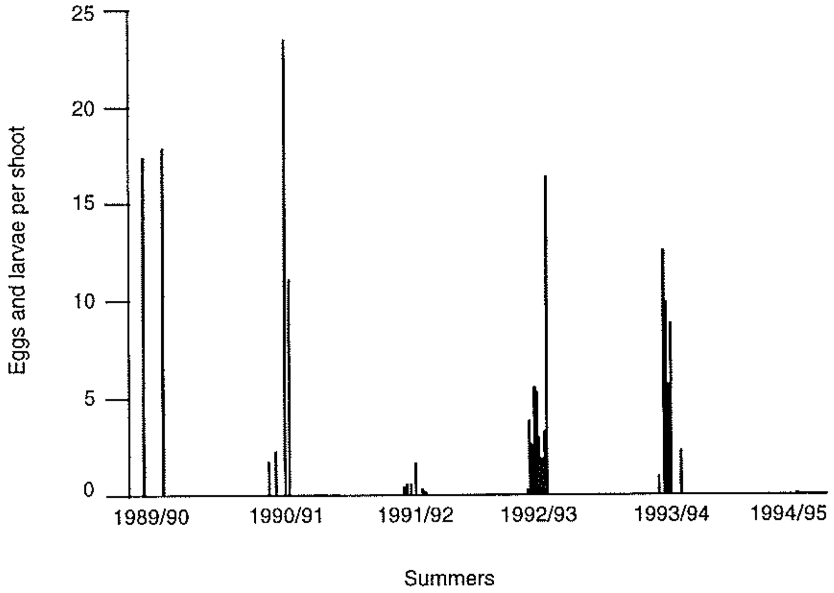

Figure 3. Estimates of populations of immature leaf beetles for six summers on the unprotected trees in the insect exclusion trial in an E. regnans *plantation (mean numbers of eggs and larvae per shoot from sampling 10 shoots on 10 trees on each occasion).*

than for unprotected trees (12.77 ± 0.55 m) (Figure 2). Protected trees had almost three times the wood volume (0.135 ± 0.03 m^3) compared with unprotected trees (0.067 ± 0.01 m^3) after eight years. Projecting this reduction in growth rate, estimated harvest time (20 years) results in a 50% reduction of potential wood production and hence significant loss in plantation value resulting from insect attack (Candy *et al.* 1992). Leaf beetles have caused some defoliation of unprotected trees every summer but their populations levels fluctuated tenfold during this period (Figure 3). These fluctuations are not reflected in the annual growth, perhaps because the impact of defoliation is spread over several years of growth (see below).

2. *Artificial defoliation trials*

A single artificial defoliation event, where over 50% of the new season's growth was removed, significantly affected growth in height, diameter and volume of three-year-old *E. nitens* for at least two years after the event (Figures 4, 5, 6). One year after the trees were manually defoliated, growth was not significantly affected by the lightest defoliation (50%) (Photo 4) but both heavy defoliation (Photo 5) and heavy defoliation plus disbudding significantly reduced height and DBH increments of trees; those with 100% of the young foliage removed were 2 m shorter, while those with 100% defoliation plus disbudding were 3 m shorter than the undefoliated trees (10.8 m). Two years after defoliation the treatment has still significantly affected height although all the defoliated trees had greater increments over the previous year than the undefoliated trees (Figure 4); only the trees with heavy defoliation plus disbudding were still 2 m shorter than the undefoliated trees (13.1 m) ($P < 0.05$). The DBH of trees that were heavily defoliated and defoliated/disbudded was still 2 cm and 3 cm respectively smaller than undefoliated trees (16.6 cm) ($P < 0.05$). Volume growth (mean annual increment) was lower in all defoliation treatments in both years but the trees in the two more

Photo 4. Eucalyptus nitens *that has been lightly manually defoliated (50% of current season's foliage removed).*

Photo 5. Eucalyptus nitens *that has been heavily manually defoliated (centre) (100% of current season's foliage removed).*

severe defoliation treatments showed some recovery in the second year after defoliation (Figure 6).

Thus, three-year-old *E. nitens* trees appear to recover from light defoliation but, when over 50% of the new season's growth is removed, they respond by increasing their growth in height but their growth in diameter (and wood volume) does not recover in the same way.

3. *Quantification of leaf beetle feeding and effect on tree growth*

Each C. *bimaculata* larva ate about 300 mg of *E. regnans* leaves or 250 mg of *E. nitens* to complete its development from egg to adult. Larvae feeding on *E. regnans* were smaller, grew more slowly and had a higher mortality rate than larvae feeding on *E. nitens* leaves (S. Baker, J. Elek and S. Candy, unpublished data). Mature adult beetles ate about 19 mg of *E. nitens* per day compared with 26 mg of *E. regnans* leaves under the same conditions (unpublished data). This suggests that *E. nitens* is a better physiological host plant for these leaf beetles, although *E. regnans* appears to be preferred over *E. nitens* for adult feeding and oviposition in the field (see below).

These results have some interesting implications for the future management of leaf beetles in *E. nitens* plantations. Although each larva eats less *E. nitens* foliage, the lower mortality rate means that more larvae survive to feed. Therefore, for a given batch of eggs, the total leaf area eaten by the greater number of survivors on *E. nitens* will be one and a half times that on *E. regnans*. In addition, if the beetles change their preference to *E. nitens* after further generations have developed on its foliage, the beetles may become a greater threat to *E. nitens* plantations than they are at present (unpublished data).

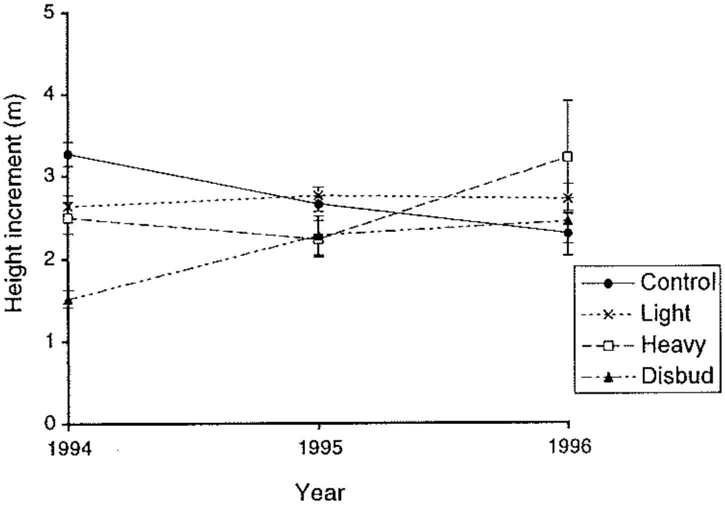

Figure 4. Comparison of the effect of different levels of severity of manual defoliation on tree height increment measured for three winters after defoliation in summer 1994. Control: no defoliation; Light: 50% of new season's foliage removed; Heavy: 100% of new season's foliage removed; Disbud: 100% defoliation followed by removal of new buds.

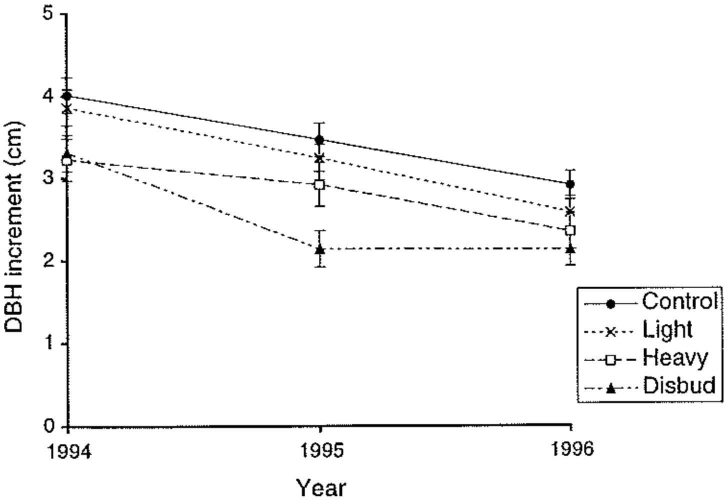

Figure 5. Comparison of the effect of different levels of severity of manual defoliation on tree diameter (DBH) increment measured for three winters after defoliation in summer 1994. Control: no defoliation; Light: 50% of new season's foliage removed; Heavy: 100% of new season's foliage removed; Disbud: 100% defoliation followed by removal of new buds.

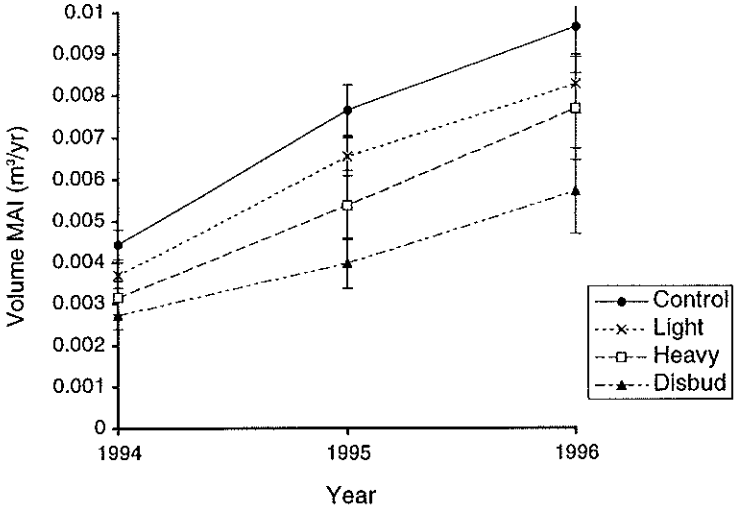

Figure 6. Comparison of the effect of different levels of severity of manual defoliation on tree volume mean annual increment (MAI) measured for three winters after defoliation in summer 1994. Control: no defoliation; Light: 50% of new season's foliage removed; Heavy: 100% of new season's foliage removed; Disbud: 100% defoliation followed by removal of new buds.

B. PEST MANAGEMENT

1. *Trap trees*

Since adults of *C. bimaculata* appear to prefer some eucalypt species, such as *E. regnans* or *E. delegatensis*, for feeding and oviposition, it may be possible to use these tree species to attract the beetles away from the less preferred plantation species. One trap-tree trial has been established in the Eastern Tiers (Dilgers Hill: 147°55'E, 41°22'S), in which four rows of *E. regnans* have been interplanted with the less preferred species, *E. nitens*. Another trial has been established in the Florentine Valley (146°28'E, 42°39'S) where *E. nitens* is interplanted with one or three rows of either *E. regnans* or *E. delegatensis*. Other operational plantations have blocks of preferred species planted next to *E. nitens*. The trials and some operational plantations are being monitored to compare the differences in beetle populations and defoliation levels between the *E. nitens* (planted on their own or adjacent to preferred species) and these trap trees.

2. *Biological insecticide*

The biological insecticide Novodor (Abbott Laboratories, supplied by Nufarm Ltd, Laverton, Victoria, active ingredient: 2% Btt) is being investigated as an alternative to the pyrethroid insecticide, Dominex 100 (active ingredient: cypermethrin 100 g/l).

The efficacy of insecticides has been shown to be related to droplet size and dispersion (Hall and Thacker 1994) and this applies also to Bt-based insecticides (van Frankenhuyzen and Payne 1993; Payne and van Frankenhuyzen 1995). These parameters are determined by the method of application. Therefore, efforts have concentrated on increasing the efficacy of Btt by testing undiluted Novodor using ULV (ultra low volume) application technology. Forestry Tasmania uses a helicopter fitted with six Micronair AU5000 rotary spray nozzles for aerial delivery of insecticides in plantations (Photo 6).

3. *Canopy-penetration trial*

A canopy-penetration trial was carried out to determine which droplet sizes and application rates of Novodor (2% Btt) would produce the best penetration into the canopy of an *E. nitens* plantation with aerial spraying (R. Bashford and B. Hodgson, unpublished data). Since canopy closure occurs in *E. nitens* plantations aged 5–7 years, the trial was carried out in an eight-year-old plantation at Smiths Plains in northern Tasmania (146°04'E, 41°26'S). Spray droplets were recorded on water-sensitive spray cards (Teejet®, Spraying Systems Co., Wheaton, IL 60189, USA) attached at different heights on artificial towers. Eight towers were erected, four pairs 20 m apart in two adjacent rows of the plantation. Cards were attached from 2 m to 10 m above the ground; the lower cards were among the foliage while the cards at 10 m were above the canopy. Spray cards were also placed to detect drift up to 160 m downwind from the flight path. Combinations of three application rates (5, 7.5 and 10 l/ha) and two nominal droplet sizes (150 and 210 μm selected by adjusting the blade angles of the Micronair spray nozzles) were tested with water, and 1:1 water to Novodor. Flight runs were 10 m above the canopy at 50 knots. Canopy penetration was determined for each run by estimating mean droplet density and diameter from the eight cards at each height above ground. The stains on the cards were adjusted to median droplet diameter (VMD) and mean droplet diameter using the spread factor multiplier of 0.45 (estimated by Novo-Nordisk Biochem North America).

4. *Aerial delivery parameters*

Spraysearch, Victoria, assessed the range of Micronair settings that would deliver undiluted Novodor (2% Btt) droplets at a size range of 50–150 μm VMD and densities of 20–30 droplets/cm^2 based on parameters used for aerial control of gypsy moth with Bt in broad-leaf forests in USA (Reardon and Wagner 1995). The settings that produced the recommended range of droplet sizes in wind tunnel tests were then tested in an aerial spray trial.

Two application rates (4 and 6 l/ha) and three blade angles (45°, 50°, 55°, which corresponded to 4100, 3500 and 3100 Micronair RPM) at 60 knots were used. Each combination was tested in one helicopter pass along 150 m at about 3 m above ground level in a paddock, with swathe widths of 12–14 m. Spray droplet size and distribution in the spray swathe were recorded on water-sensitive spray cards set out in five rows 25 m apart along the swathe, with 14 cards in each row. Drift was recorded for 150 m downwind from the flight line. Temperature, humidity, wind speed and direction were recorded for each run. Spray cards were analysed by Spraysearch and the stains on the cards were corrected to droplet size VMD using a spread factor of 0.45.

5. *Operational spray trials*

The efficacy of undiluted Btt for controlling *C. bimaculata* in eucalypt plantations was tested in two operational field trials using undiluted Novodor (2% Btt), with the delivery setting of 45° blade angle which corresponded to 4050–4150 RPM at a helicopter air speed of 60 knots. Both trials were carried out in a six-year-old plantation of *E. regnans*, mean height about 5 m, in north-eastern Tasmania (Eastern Tiers, Evercreech compartment 15: 147°55'E, 41°23'S). The spray droplet sizes and densities, temperature, humidity, wind speed and direction were recorded during the spraying.

In the first trial, Novodor was sprayed at two application rates (4 and 6 l/ha) while an adjacent area was left unsprayed. Before spraying, shoots with batches of eggs and first or second instar (L1 or L2) larvae of *C. bimaculata* were tagged on 15 trees in each of the sprayed areas and 10 trees in the unsprayed area. Before spraying, and four days after it, the immature leaf beetle population (mean number of insects per shoot) was assessed on trees in all three areas.

After spraying, half the tagged shoots with the immature stages were returned to the laboratory, where they were fed and monitored every two days for mortality and development until all the larvae had either died or emerged as adults. The mean mortalities were corrected with Abbott's Correction using the mean mortality from the unsprayed area. The other half of the tagged

Photo 6. Measuring the flow rate of the biological insecticide Novodor. The helicopter is fitted with six Micronair AU-5000 rotary nozzles which deliver the insecticide to the plantations.

shoots were left in the field and larval mortalities monitored four days later.

The second trial was carried out in the same plantation two weeks after the first trial, using the same helicopter delivery platform. Novodor was applied at 6 l/ha and 12 l/ha, with an adjacent area left unsprayed.

Before spraying, shoots with immature stages of *C. bimaculata* were tagged on 15 trees in the two spray areas. Per tree, one shoot for each stage was returned to the laboratory as an unsprayed laboratory control and one shoot for each stage was covered with a plastic bag to protect it from the spray, to be used as an unsprayed field control (Photo 7). The immature leaf beetle population was assessed in the two sprayed areas and in the unsprayed area. After spraying, another shoot for each stage was returned to the laboratory where eggs and larvae were monitored every second day as in the previous trial. Other shoots with each stage were left in the field.

Four days after spraying, mortalities of the sprayed and unsprayed larvae on the tagged shoots left in the field were monitored and corrected for natural mortality using the unsprayed field control shoots. The immature populations on trees in the three areas were also assessed. These estimates needed log transformation for statistical analyses: log (mean larvae per shoot + 0.01).

Photo 7. Shoots covered with plastic bags to act as unsprayed field controls.

Results and discussion

1. Trap trees

The *E. nitens* in the Eastern Tiers trial had adult foliage in the summer of 1995/96 but the plantation had received no significant leaf beetle attack. Although the *E. nitens* in the Florentine Valley had no adult foliage in 1995/96 and no leaf beetle attack, the interplanted *E. delegatensis* did receive sufficient egg laying from *C. bimaculata* to warrant protective spraying.

The *E. nitens* monitored in the Plenty Valley had significantly lower populations of *C. bimaculata* throughout January and insignificant defoliation compared with the adjacent *E. regnans* (Figure 7).

2. Biological insecticide

A comparison of Btt (Novodor) with cypermethrin (Dominex 100) has shown that, although the population of *C. bimaculata* larvae was reduced only 56.8% by Btt (using a 50% dilution of Novodor 2%) compared with 100% reduction by cypermethrin, both insecticides reduced the amount of leaf area eaten to the same extent (Elliott *et al.* 1992); shoots treated with either Btt or cypermethrin had three times the leaf area remaining on untreated shoots.

The toxicity of Btt to the main egg and larval predators, coccinellids and cantharids, has also been assessed. There was no effect on coccinellid adults and older larvae but the longevity of cantharid adults may be affected (Greener and Candy 1994). However, the cantharids are present only during the early part of the summer and so are unlikely to be affected by any spraying during mid summer.

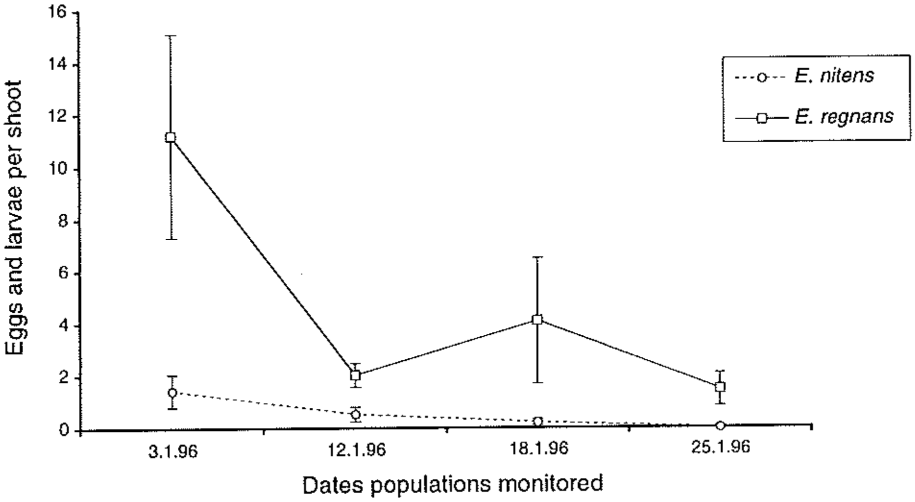

Figure 7. Comparison of populations of immature leaf beetles on adjacent E. nitens *and* E. regnans *in the Plenty Valley (mean numbers of eggs and larvae per shoot from sampling at least 10 shoots on 10 trees of each species on each occasion).*

Table 1. Spray parameters used and the resulting droplet sizes and densities of water and diluted Novodor 2% (active ingredient Bacillus thuringiensis *var.* tenebrionis *protein) at different heights in the canopy of* E. nitens *in the canopy penetration trial (R. Bashford and B. Hodgson, unpublished data). (VMD = median droplet diameter)*

Spray	Application rate (l/ha)	Target median droplet diameter VMD (µm)	Actual median droplet diameter VMD (µm)	Actual mean droplet diameter ± SE (µm)	Droplet densities (per sq cm) at heights (m) above ground				
					2	4	6	8	10
Water	5	160	151	132 ± 4.8	1.7	2.1	2.5	3.3	9.9
Water	5	220	194	169 ± 5.0	1	1.8	2.7	3.3	5.3
Water	7.5	215	237	205 ± 5.7	1.3	1.1	1.8	1.9	5.5
Water	10	155	151	158 ± 3.4	6.4	4.8	8.1	12.3	15.9
Water	10	215	194	144 ± 5.2	1.5	2.2	1.5	4.4	9.1
Water:Bt	10	155	65	148 ± 5.2	0.8	1.9	1.9	5	8.9
Water:Bt	10	215	194	192 ± 3.8	3.7	5.7	6.7	12.8	23.3

3. *Canopy penetration trial*

The actual droplet median diameters (VMDs) were almost all smaller than the nominal target VDMs, and the mean diameters were smaller still. In some cases, the actual VMD and the mean were inversely related, perhaps because the distribution of droplets was skewed towards the smaller diameter droplets. In all runs, droplet densities decreased from 10 m to 2 m above ground level (from three- to elevenfold) (Table 1). In some runs, there were fewer droplets at 4 m than 2 m. The highest droplet densities and the largest droplets were produced by the highest application rate (10 l/ha). This was not expected because generally larger droplets will be at lower densities than smaller droplets at the same

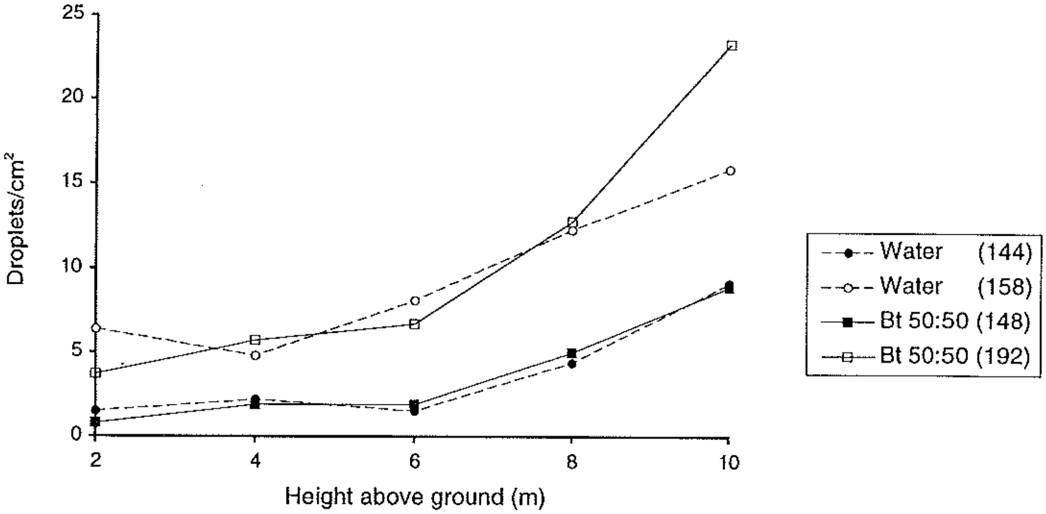

Figure 8. A profile of the density of droplets of water and water:Novodor 2% (active ingredient Bacillus thuringiensis *var.* tenebrionis *protein) at different heights in the canopy of eight-year-old* E. nitens *trees after aerial spraying to test canopy penetration. (Bracketed figures in the legend are mean droplet diameters; see Table 1.)*

application rate (Sundaram and Sundaram 1987); many of the smaller droplets may have drifted away as the distribution of the droplets detected on the drift cards up to 140 m downwind of the flight path was skewed towards the smallest diameters. The best penetration was also achieved at 10 l/ha with the larger mean droplet sizes for both water (density decreased threefold from 10 m to 2 m height above ground) and for 50% Novodor (density decreased sixfold from 10 m to 2 m height) (Figure 8).

4. *Aerial delivery parameters*

During the aerial spraying trials, wind speeds varied from 0 to 6 km/hr; temperature ranged from 11 to 18°C and relative humidity varied from 65% to 90% at 1.5 m above ground. Size and density of droplets across the 14 m swathe spray were greater for the 6 l/ha treatment than for the 4 l/ha treatment (Table 2). Many of the droplets were within the desired size range of 50–150 µm, but the distribution was skewed towards the smaller diameters. The median range for the three runs was 18–54 µm at 4 l/ha and 18–72 µm for 6 l/ha. All runs produced less than 3 droplets/cm^2 (> 10 µm diameter) on drift cards, with less than 1/cm^2 beyond 93 m. Thus, the Micronair rotary spray nozzles successfully delivered undiluted Novodor 2% within the recommended range of droplet diameters 50–150 µm VMD at application rates of 4 l/ha and 6 l/ha.

5. *Operational spray trials*

During the first spray trial, weather conditions during the spraying were: temperature 15–16°C, relative humidity 50–52% and wind speed 0–6 km/hr. Analysis of the droplet density and size on the cards showed that the mean density was 12.5 ± 1.6 droplets/cm^2 for 4 l/ha and 25.7 ± 6 droplets/cm^2 for 6 l/ha. The diameter of most droplets for both applications ranged between 20–90 µm, with the VMDs of 27 µm (after adjusting for the spread factor of 0.45).

Novodor caused significant mortality of the eggs and L1 and L2 stages of *C. bimaculata* that had been returned to the laboratory; this increased with higher application rates but decreased as the age of treated larvae increased. Many eggs failed to hatch in the laboratory due to fungal contamination so that the larvae which hatched from treated eggs died after eating the egg chorion.

Table 2. Application rates, helicopter settings and the resulting droplet sizes and densities of undiluted Novodor 2% tested across a swathe of 14 m in aerial spray trials.

Btt application rate	Micronair RPM	Micronair blade angle	Height above ground (m)	Droplet modes	
				Size VMD (μm)	Range (no./sq cm)
4 l/ha	4100	45°	3	45	6–17
	3500	50°	3	27	10–15
	3100	55°	3	27	5–11
6 l/ha	4100	45°	3	27	18–33
	3500	50°	3	63	21–36
	3100	55°	8	45	6–19

Both the Novodor application rates and the stages sprayed significantly affected larval mortality four days after spraying and at adult emergence (both $P < 0.01$) (Table 3).

Although Novodor caused significant mortality of the insects that were sprayed in the field but monitored in the laboratory, it did not have comparable effects on the populations monitored in the field. Novodor did not reduce the numbers of immature insects in the sprayed areas relative to the unsprayed area. One reason for these results may have been the different age structure of the populations and different levels of natural mortality in the three areas. De Little *et al.* (1990) have shown that 84% of eggs can be lost to natural causes.

Thus, laboratory monitoring showed that 6 l/ha Novodor sprayed operationally killed over 99% of eggs and L1 larvae, but only 55% of L2 larvae. However, Btt did not significantly reduce the field populations at either application rate compared to the levels of natural mortality.

In the second trial, the weather conditions during spraying were: temperature 15°C, relative humidity 36–40% and wind speed 0–2 km/hr. The spray droplet density was lower than in the previous trial; mean droplet densities were 17.8 ± 1.3 droplets/cm^2 for the 6 l/ha treatment and 32 ± 3.3 droplets/cm^2 for the 12 l/ha treatments. The diameter of most droplets was slightly higher, ranging from 20 to 70 μm for the 6 l/ha treatment and from 40 to 110 μm for the 12 l/ha treatment, with VMDs of 27 μm and 45 μm for the 6 l/ha and 12 l/ha treatments respectively.

Four days after spraying, both the application rate of Novodor and the stage of larva sprayed had significant effects on the mortality of the larvae monitored in the laboratory (both $P < 0.01$) as in the first trial (Table 3). The overall corrected mortality for the three stages was lower than in the previous trial.

At adult emergence, mortality in the laboratory was much higher for all stages, being only a little lower than in the previous trial. Both application rates of Novodor caused significantly higher mortalities than those of unsprayed larvae, but there was no statistical difference between the effects of the two rates. The stage sprayed also had a significant effect on larval mortality at adult emergence ($P = 0.013$).

The mortality of sprayed larvae monitored in the field was also significantly higher than that of unsprayed larvae, but there were no differences between application rates. Four days after spraying, the mortality of all larvae monitored in the field was higher than that of laboratory larvae for all stages and application rates: 60% higher for 6 l/ha and 17% higher for 12 l/ha ($P = 0.04$) (Table 3). The higher field mortalities of sprayed larvae may have been due to natural mortalities

Table 3. Mean corrected mortality of larvae in two operational spray trials for three stages sprayed. After being sprayed in the field, 'laboratory larvae' were brought into the laboratory and monitored; 'field larvae' remained in the field and were monitored there. Egg mortality refers to neonates which died after eating the egg chorion. Standard errors could not be calculated for corrected mortalities in Trial 1. Correction for natural mortality used Abbott's correction factor: corrected mortality T - C = (100 - C) x 100, where C = % mortality of unsprayed larvae, and T = % mortality of sprayed larvae.

	Mortality %						Mean total mortality (%) for all stages	
	Four days after spraying			At adult emergence				
Application rate (l/ha)	Egg (SE)	L1 (SE)	L2 (SE)	Egg (SE)	L1 (SE)	L2 (SE)	Four days (SE)	At end (SE)
Trial 1								
Laboratory larvae								
4	37.82	73.21	21.81	100	95.03	46.54	44.28	80.52
6	62.15	87.98	31.7	100	99.35	54.96	60.61	84.77
Trial 2								
Laboratory larvae								
6	22.75	84.48	23.88	100	100	69.12	43.70	89.71
	(9.18)	(9.50)	(9.18)	(10.06)	(5.58)	(5.19)	(5.36)	(4.21)
12	73.30	72.15	62.56	100	94.34	92.98	69.34	95.77
	(10.26)	(10.26)	(11.85)	(7.11)	(6.07)	(7.11)	(6.24)	(3.92)
Field larvae								
6	71.24	61.68	78.10				70.34	
	(11.22)	(12.40)	(11.22)				(6.71)	
12	95.38	100	48.00				81.13	
	(14.06)	(16.64)	(16.64)				(9.14)	

such as predators and parasitoids in the field. This was suggested by higher mortalities of unsprayed larvae in the field (61%) compared with those in the laboratory (24%).

In contrast to the significant effect of Novodor on mortality of the larvae monitored in both the laboratory and the field, the assessments of field populations showed no effect of Novodor spray. In all treatments (unsprayed, 6 l/ha, 12 l/ha), populations decreased significantly after spraying ($P < 0.01$), but there were no differences between unsprayed and sprayed areas ($P = 0.47$). This indicates that the decrease in population was not caused by the Novodor spraying but by natural causes.

The populations in all areas before spraying corresponded to 50, 58 and 72% of shoots, with at least one occupied leaf per shoot, which is below the minimum threshold of 100% occupied shoots currently used at Forestry Tasmania to initiate insect control measures in *E. regnans.* At this relatively low population level, consisting mainly of eggs and young larvae, the Novodor spray appears to have caused levels of mortality similar to those caused by natural factors, such as predation and parasitism. Natural mortality levels of 95–97% over all stages (egg to L4) have been recorded (de Little *et al.* 1990).

Therefore, at low populations levels of *C. bimaculata*, it appears that Btt-based Novodor will be no more effective than the natural mortality factors at reducing larval numbers in the field. However, at high population levels, Novodor may be effective at reducing the larval numbers to a level that can be controlled by natural mortality factors and so be reduced below the minimum threshold that causes economic damage to plantations. In addition, since Btt has an anti-feedant effect, it may also reduce the amounts of foliage consumed by the surviving larvae. Further trials will be carried out to test these hypotheses.

Conclusions

Insect defoliation causes significant reduction in growth rate of *E. regnans* trees, projected over 20 years to reduce wood volume by up to 50%. Trials using artificial defoliation indicate that one defoliation of three-year-old *E. nitens* trees of more than 50% of the current season's foliage causes significant loss of growth and wood volume over two years. Although the leaf beetles prefer other tree species to *E. nitens*, feeding trials showed that their larvae eat less but survive better on *E. nitens*. However, the larger number of survivors will eat 1.5 times the foliage of *E. nitens* compared to that of *E. regnans*. Interplanting of more preferred species may act as trap trees or as early warning for monitoring large populations of leaf beetles.

Tests with a biological insecticide indicate that the Btt-based bioinsecticide Novodor can be aerially sprayed using ULV technology to reduce populations of *Eucalyptus* leaf beetle larvae. Mortality decreased with age of larvae sprayed and increased with application rate of Novodor, but there was no significant difference between 6 l/ha and 12 l/ha application rates. About 50% of young larvae were killed within four days of spraying, and 90% died before completing their development. Novodor sprayed on low populations of larvae in the field did not reduce the population more than natural mortality factors in the unsprayed areas. However, when larval populations are high, Novodor may supplement the natural predation by reducing the numbers of larvae to a level that can be controlled by natural mortality factors. Novodor has good potential for controlling insect browsing and maintaining levels of defoliation below the economic threshold because it is compatible with other methods employed in integrated pest management and it complements the levels of natural mortality due to predators and parisitoids.

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