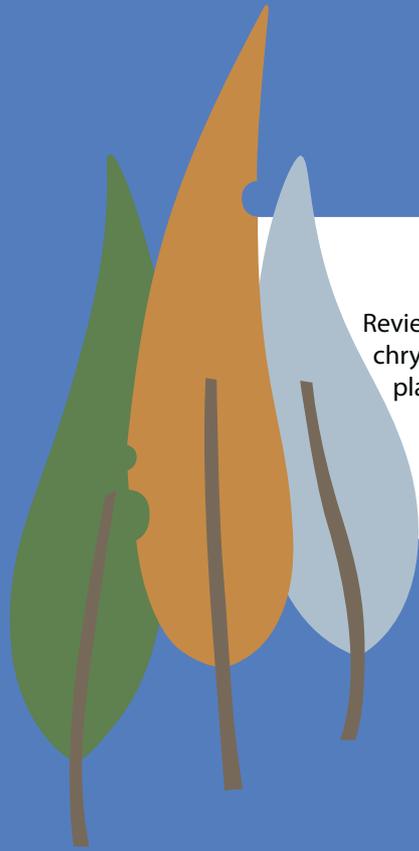


Managing and monitoring for growth and health



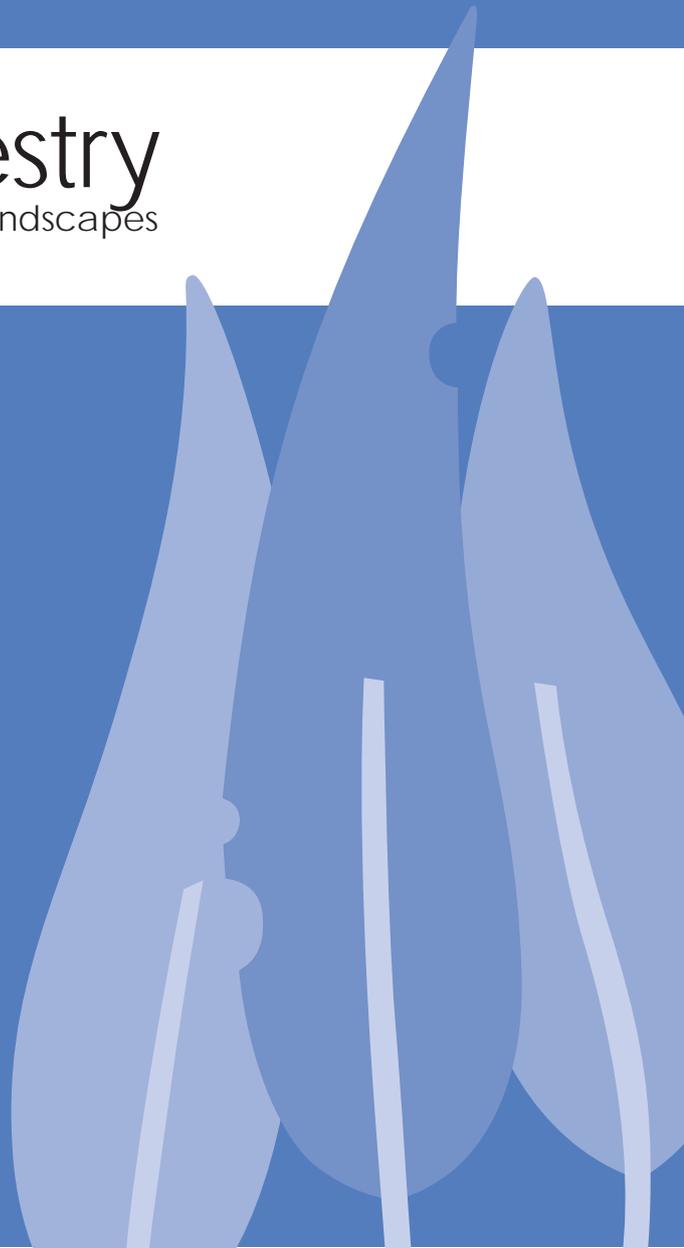
Technical Report 204

Review and evaluation of options for managing
chrysomelid leaf beetles in Australian eucalypt
plantations: Reducing the chemical footprint

Public report

By J Elek ^{1,2}, T Wardlaw ^{1,2}

CRC for Forestry
Researching sustainable forest landscapes



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Contents

Research highlights.....	1
Abbreviations	1
Abstract.....	2
Introduction	4
Review of pest management options	7
<i>Landscape management for augmenting natural controls</i>	7
Tree improvement.....	7
Conserving natural enemies.....	10
Conserving overwintering sites for natural enemies.....	12
Alternative sources of food and hosts for natural enemies.....	12
Silviculture regimes to minimise impact of defoliation	14
Trap trees	17
Lethal trap trees.....	18
Combining repellent and attractant plants: 'Push-pull' concept	19
<i>Controlling outbreaks</i>	20
Modify use pattern of insecticides	20
Replace broad-spectrum with softer insecticides for aerial spraying	20
Time insecticide sprays to minimise impact on natural enemies.....	22
Different application technologies and formulations.....	22
Biological control	23
Classical biological control	23
Enhance natural diseases	24
Rear and release natural enemies	25
Artificial attractants or repellents for pests or natural enemies	25
Artificial food attractants.....	26
Repellents	26
Infochemicals.....	26
Attract-and-kill traps.....	28
Evaluation of management options	29
Methods	29
Results	30
Discussion	32
Acknowledgments	37
References.....	38
Table 1: Summary table of scores for ranking 17 chrysomelid management options for five criteria, sorted under 'landscape' and 'control' options.....	56

Research highlights

- Options for managing chrysomelid leaf beetles to prevent economic damage to eucalypt plantations in Australia have been reviewed and evaluated under ‘landscape’ and ‘control’ options.
- The option ranked most highly overall was the ‘landscape’ option of tree improvement to develop trees less susceptible or more tolerant to herbivory, so research into this option is a priority.
- Attract-and-kill traps was the most highly ranked ‘control’ option, with lethal trap trees recommended as a pathway for evaluating these traps.
- No single option alone was considered capable of preventing economic damage. Successful integrated pest management would include implementing a range of ‘landscape’ options to reduce the frequency of outbreak populations, with ‘control’ options used if population outbreaks occurred.

Abbreviations

AFS	Australian Forestry Standard, has mutual recognition by PEFC
FSC	Forest Stewardship Council
IPM	Integrated pest management
ISO	International Organization for Standardization; ISO 14001:2004 specifies requirements for an environmental management system to enable an organization to develop and implement a policy and objectives which take into account legal requirements and other requirements to which the organization subscribes, and information about significant environmental aspects. It applies to those environmental aspects that the organization identifies as those which it can control and those which it can influence. It does not itself state specific environmental performance criteria.
PEFC	Programme for the Endorsement of Forest Certification

Abstract

Chrysomelid leaf beetles are a major defoliating pest of plantation eucalypts in Australia and require active management. In Tasmania, an integrated pest management (IPM) system is used to manage two leaf beetle species—*Paropsisterna bimaculata* and *P. agricola*. Egg and larval populations are monitored routinely in young plantations. When control by natural enemies is inadequate and populations are predicted to exceed an economic injury threshold, then a broad-spectrum insecticide is aerially sprayed to prevent loss of wood volume. An extensive literature review was undertaken that documented the current state of knowledge on the potential options for managing leaf beetles that would reduce reliance on, or eliminate the use of, aerial spraying with broad-spectrum insecticides to prevent economic injury to eucalypt plantations. The options fell into two groups:

- ‘landscape’ options—that reduce the frequency of pest outbreaks that would require control, and
- ‘control’ options—for managing pest outbreaks in plantations that are predicted to cause economic damage when they occur.

Each option described in the review was evaluated by nine Australian scientists with expertise in forest pest management. They compared all the options against a baseline of managing pest outbreaks by aerial spraying with a broad-spectrum insecticide, and evaluated them against five criteria:

- effectiveness in reducing insect populations below levels that would be economically damaging
- feasibility for operational use
- impact on the environment
- perceived social acceptability
- perceived cost.

All scores were summarised and the options were ranked within the two groups (‘landscape’ and ‘control’ options) and overall.

None of the options were scored as well as the baseline for effectiveness, feasibility and perceived cost, but virtually all were scored better for improved environmental and perceived social outcomes.

The two options with the highest ranks were the ‘landscape’ option of tree improvement for improved resistance to or tolerance of insect attack, and the ‘control’ option of attract-and-kill traps.

The next four ranks were all ‘landscape’ options with high scores for feasibility, improved social and environmental outcomes and cost:

- maintenance of overwintering sites for natural enemies
- providing alternative food and hosts to enhance natural enemy populations
- silvicultural management
- lethal trap trees deployed in high-risk areas.

Although they were considered to be less effective, ‘landscape’ options should be additive so each should help reduce the frequency of outbreaks.

Lethal trap trees were considered to be the most effective of the ‘landscape’ options, after tree improvement. The experts considered that they would also be useful as a pathway to the development of attract-and-kill traps. The option of substituting softer insecticides for a broad-spectrum insecticide was considered to be the most effective alternative ‘control’ option, although it was perceived to have low social acceptability. This was due to their application by broad-acre aerial spraying. However, spraying softer insecticides is the only alternative ‘control’ option currently available.

No single option was considered adequate for preventing economic losses. The best strategy for an IPM program would be a combination of ‘landscape’ options to reduce the frequency of pest outbreaks and, if outbreaks occur, deploying attract-and-kill traps when available, possibly in combination with repellent sprays in a push–pull strategy, or spraying with softer, biological insecticides.

This review has identified high-priority research areas needed before many options could be used operationally. These are:

- Investigate the heritability and stability of variation in defoliation levels in response to leaf beetle populations; correlate these with existing traits for growth and resistance to other pests and diseases. Use conventional tree improvement to develop planting stock that repels, is resistant to or, at least, is more tolerant of defoliation.
- Develop the technology and expertise to create lethal trap trees that effectively attract and kill the main leaf beetle pests, then determine their effectiveness at protecting plantations from defoliation.
- Identify and evaluate infochemicals from plants and beetles that would lead to the development of attract-and-kill traps and/or repellents.
- Develop protocols for retaining standing dead trees that do not pose a safety risk to workers in plantations, and for fertilising plantations to reduce loss of growth following defoliation.
- Evaluate existing literature on the effectiveness of increased plant diversity within and surrounding plantations for providing food and shelter for natural enemies, thereby reducing the incidence of pest outbreaks; identify and target the gaps in the research.

Introduction

In many areas of Australia, paropsine leaf beetles (Chrysomelidae: Chrysomelinae) have become recognised as major defoliator pests of eucalypt plantations (Elliott et al., 1998). More than 400 species in eleven genera are native and feed on eight native plant genera throughout Australia. All but one of the plant genera are in the Myrtaceae family, which includes *Eucalyptus* and *Corymbia*. Of these paropsines, twelve species have been recorded as pests of *Eucalyptus* species in Australia (Simmul and de Little, 1999). Both adult beetles and larvae of all paropsine species are foliage feeders. In Queensland, of 17 paropsine chrysomelid species collected from three major plantation species, *E. dunnii*, *E. cloeziana* and *Corymbia citriodora*, four species were abundant: an unidentified *Paropsisterna* species, *P. cloelia*, *Paropsis charybdis* and *P. atomaria* (Nahrung, 2006). Of these, *P. atomaria* has the greatest potential to emerge as a serious pest in eastern Australia with genetically similar populations throughout its wide geographic and host range (Carne, 1966; Nahrung et al., 2008a). In Western Australia, although paropsines have not been reported as being serious pests of the 'introduced' *E. globulus* plantations, they have the potential to increase their impacts (Loch and Floyd, 2001). Introduced *P. charybdis* has become a serious pest of eucalypt plantations in New Zealand (de Little 1989; Withers, 2001) and an undescribed species (*Paropsisterna* nr. *gloriosa*) recently established in Ireland is rapidly becoming a pest of eucalypt plantations there (Horgan, in press). Chrysomelids in the Cryptocephalinae subfamily, *Cadmus* spp., can also be intermittent pests, particularly in Western Australia and parts of northern Tasmania; however, only the adults have pest potential as their larvae feed on leaf litter (Loch and Floyd, 2001).

Leaf beetles in the Chrysomelinae sub-family have long been considered chronic pests of Tasmanian eucalypt forests (Greeves, 1966; Bashford, 1993) and have the highest incidence of all insect pests recorded in *E. globulus* and *E. nitens* plantations (de Little et al., 2008). Of 31 paropsine chrysomelid beetle species recorded from *Eucalyptus* spp. in Tasmania, 7 have been recorded from the native *E. globulus* and 20 from the introduced plantation species *E. nitens*. Four *Cadmus* spp. (Cryptocephalinae) were also recorded from these plantation species (Tasmanian Forest Insect Collection, October 2009, pers. comm., Lynne Forster). Of the 20 chrysomelinae species recorded from the two plantation species, only two have become pests that require management in Tasmanian plantations: *Paropsisterna bimaculata* (Olivier) and *P. agricola* (Chapuis) (formerly *Chrysophtharta* spp.). An analysis of the biotic and abiotic factors affecting performance of *E. nitens* and *E. globulus* plantations in Tasmania determined that chrysomelid defoliation, primarily by *P. bimaculata* and *P. agricola*, was the most common problem (Wardlaw, 2010). These two species are distributed throughout Tasmania from sea level to the tree line, wherever suitable host trees occur (de Little and Madden, 1975). *P. agricola* also occurs in southern mainland Australia (Nahrung, 2002). Both the larval and adult beetles of these species target the tender new growth of established, healthy trees (de Little, 1983; Howlett et al., 2001; Lawrence et al., 2003; Nahrung, 2004). The establishment of large areas of vigorously growing eucalypt plantations may have increased the problem by providing resources in excess of those available in native forests (Strauss, 2001). There is some evidence that *P. agricola* has extended its range recently into

southern Tasmania coincident with the expansion of *E. nitens* plantation establishment (Nahrung, 2004). Restricted gene flow among *P. agricola* populations within Tasmania and high heterogeneity within local populations suggest that they have limited dispersal, for example between populations from the Florentine Valley and Ellendale in southern Tasmania, only 17 km apart (Nahrung and Allen, 2003). In contrast, *P. bimaculata* have a patchy distribution and disperse widely over more than 100 km; they usually feed and lay one batch of eggs before moving the following week to another area more than 100 m away to continue their activities (Clarke et al., 1997; Congdon et al., 1997).

Chrysomelids are likely to have co-evolved with eucalypts over a long period of time, concurrently with a suite of natural enemies (predators and parasitoids) that help regulate chrysomelid populations, such that outbreaks causing severe damage of native forests are uncommon. Natural enemies are also very important for maintaining populations of chrysomelids in plantations below damaging levels most of the time. The majority of *P. bimaculata* and *P. agricola* mortality is due to predation during the egg and first instar larval stages, with some parasitism of eggs and larvae (de Little, 1982; de Little et al., 1990; Nahrung and Murphy, 2002; Nahrung and Allen, 2004a; Rice, 2005). However, the time lag of the fluctuations in natural enemy populations in response to pest populations means that natural enemies cannot prevent all outbreaks.

Chronic leaf beetle feeding that slows the growth rate of vigorously growing young trees may be acceptable in native forest but not in plantations, where the primary objective is to maximise wood production. The main aim of insect pest management is to prevent significant losses of wood quantity. The forest industry is fortunate that the quality of the end product, wood fibre or timber, is not compromised by low levels of chrysomelid damage. In addition, low levels of damage can be tolerated since eucalypts appear to be able to compensate for up to 25% loss of current season's foliage (Pinkard et al., 1999, Pinkard, 2003). However, defoliation exceeding 50% of the newly expanded, upper-crown foliage can significantly reduce growth rates for up to four years after the defoliation event (Candy et al., 1992; Elek, 1997; Candy, 1999; Collett and Neumann, 2002; Pinkard et al., 2006a and b). Rapley et al. (2009) projected 25% loss of *E. nitens* growth at harvest after 60–80% of the crown of 3-year-old trees were defoliated once by autumn gum moth. The growth impact can be more severe if defoliation occurs in autumn or for more than one consecutive season (Candy et al., 1992; Elek, 1997). Candy (1999) projected that uncontrolled, chronic defoliation by leaf beetles over the rotation of an *E. regnans* plantation could reduce wood volume at harvest by up to 50%.

Forestry Tasmania uses an integrated pest management (IPM) program to manage leaf beetle damage. The IPM program is designed to capture maximum benefit from the natural enemies. The decision to control populations is made only after the natural enemies have had a chance to predate eggs and neonates, and is based on whether the monitored larval populations are above a defined economic impact threshold. The control operation is generally aerial spraying with a broad-spectrum insecticide to reduce larval populations before they reach the third and fourth instar stages, which cause the most damage (de Little, 1983; Elliott et al., 1992; Elliott et al., 1998). Controlling larval populations does not prevent reinvasion of plantations

by adult beetles from surrounding forests because the beetles are very mobile (Clarke, 1995; Clarke et al., 1997). This means that an IPM program on controlling larval populations may not adequately protect plantations from adult feeding damage later in the season.

Forest health surveys of Forestry Tasmania's plantation estate have shown that the IPM program prevents a considerable amount of economically injurious defoliation. About 40% of the estate (all plantations 3–7 years old) is monitored for leaf beetle populations throughout the summer. During the 2005–2009 seasons, leaf beetle populations were above the defined economic-damage threshold in 30% of the monitored area; an average of 68% of the area over-threshold was sprayed with insecticide while the remaining area either fell below the threshold as a result of natural controls or could not be sprayed due to environmental or logistical constraints. Only 13% of the sprayed area was treated using an insecticide with low environmental impact; the remaining area was sprayed with a broad-spectrum pyrethroid insecticide. During the 2008–2009 season, 6% of the total plantation estate area suffered more than 25% defoliation of the crown, three-quarters of which was caused by defoliation during autumn by the first-generation adult beetles (Forestry Tasmania, 2009, p. 37 and Appendix 2, p. 13). Thus, controlling the larval populations is reducing most but not all the defoliation damage, with adult beetles feeding during autumn still causing some economic damage.

Many forest managers are striving for their forest production areas to be certified under FSC or PEFC-affiliated AFS that require forest managers of certified forests to protect forests from damaging pests, while also producing wood economically. FSC further challenges managers to reduce, with the aim of eliminating, the use of non-biological insecticides for protecting plantations. In addition, social pressures are restricting the broad-scale use of insecticides. Even environmentally friendly insecticides soon may not be acceptable when aerially sprayed.

Sole reliance on aerially applied broad-spectrum insecticides as the primary method for managing outbreak populations is therefore a high business risk for forest managers.

To reduce this risk we need to find alternative methods of managing leaf beetles in Tasmanian eucalypt plantations that do not involve aerial spraying with broad-spectrum insecticides and which reduce the chemical footprint. The authors conducted a review of the world-wide literature to find potential alternative pest-management strategies in forestry and agriculture, as well as following up novel pest-management proposals at recent entomological conferences.

This report is in two parts. The first part summarises the many potential options for managing leaf beetle defoliation and includes examples of implementation for any forestry applications as well as related agricultural pests, such as the chrysomelid Colorado potato beetle.

The management options have been categorised under two main categories:

- **'landscape' options** that reduce the incidence of pest outbreaks
- **'control' options** for managing pest outbreaks in plantations when they occur.

The second part describes the evaluation and rating of the potential management options, against a baseline of aerial spraying with broad-spectrum insecticides, by a panel of scientists with expertise in managing forest pests and diseases. The options were scored for their

expected operational effectiveness and feasibility in reducing larval and adult leaf beetle populations below levels that would be economically damaging, as well as their expected environmental, social and economic (triple bottom line) outcomes. They were then ranked overall as well as within the two categories of management options. These rankings inform recommendations for future research into alternative management strategies.

Review of pest management options

Landscape management for augmenting natural controls

Landscape management options are reviewed under five main headings: tree improvement, conserving natural enemies, silviculture regimes, trap trees and combining repellent and attractant plants in a 'push-pull' concept.

Tree improvement

Breeding for specific traits in long-lived tree species is a slow and expensive process, but screening existing stock and deploying those lines that are least susceptible to defoliation may be a much more rapid method of transferring genetic gains to plantations. Selection of clones can be a much more rapid process. Planting resistant stock is the primary method recommended for managing insect pests in North American hardwood plantations (Coyle et al., 2005), perhaps because the commonly planted species can be cloned easily from cuttings. For example, insect-resistant clones have been identified in *Populus* and *Picea* spp. (Coyle et al., 2002; Cocq et al., 2005). The only known example of selection and deployment of plantation seed stock resistant to insect herbivores in Australia is selection of *Pinus radiata* for resistance to the Monterey pine aphid, *Essigella californica* (Sasse et al., 2009).

The primary focus of tree improvement of plantation eucalypts in Australia currently is on selection for traits conferring favourable growth and wood properties. Rather than add a new trait for resistance to herbivory into the selection process that may slow the rate of genetic gain in these traditional traits, another strategy would be to screen the existing breeding stock to eliminate races, families or genotypes that are particularly susceptible to the pest(s) of concern (pers. comm. Dean Williams, Forestry Tasmania, February 2010). However, there could be a metabolic cost to resistance which could result in lower growth rates of resistant trees in the absence of herbivory (pers. comm. Brad Potts, University of Tasmania, July 2010). If there is a cost to resistance, then such selections would need to be targeted for deployment in areas of known high risk of leaf beetle herbivory. Alternatively, since defoliation can affect growth rates of trees (Candy et al., 1992), selection of trees with the best growth rates in trials that suffer uncontrolled leaf beetle defoliation should also select for resistance or tolerance to herbivory, assuming tolerance of defoliation has high levels of heritability.

Enhanced resistance to leaf beetle herbivory could be mediated by pre-existing, constitutive physical or chemical traits that confer resistance, or could be rapidly induced following exposure to the pest. In eucalypts, although diseases that invade the trunk induce chemical and physical responses (Eyles et al., 2003), there has been little evidence to date that defoliating insects induce resistance. Resistance to defoliating insects is thought to be mainly due to structures or secondary metabolites that are expressed constitutively rather than induced

(Henery et al., 2008a and b; Rapley et al., 2008). Variation in insect defoliation in eucalypts has been shown to be under some level of genetic control, both between and/or within provenance (e.g. positive narrow-sense heritabilities, h^2) (Farrow et al., 1994; Raymond, 1995; Jordan et al., 2002; Rapley et al., 2004a). Some traits that render eucalypt trees more or less attractive or susceptible to certain eucalypt herbivores have been identified, for example leaf colour, toughness, and specific oils or surface waxes (Raymond, 1998; Edwards et al., 1993; Steinbauer et al., 1998; Jones et al., 2002; Lawrence et al., 2003; Steinbauer and Matsuki, 2004; Steinbauer et al., 2004b; Östrand et al., 2008; O'Reilly-Wapstra et al., 2004; Rapley et al., 2004b). Foliar near infra-red reflectance (NIR) spectra that measure the overall chemical composition were able to discriminate between eucalypt families with low and high levels of defoliation, suggesting that NIR could have potential for predicting resistance (Henery et al., 2008a).

There has been some work on heritability of traits associated with herbivory by Tasmanian chrysomelids. Raymond (1995) reported a heritability (narrow-sense h^2) of 0.48 ± 0.08 among *Eucalyptus nitens* families and provenances for susceptibility to defoliation by *Paropsisterna bimaculata*. The 'Toorongo-early adult' provenance was most susceptible to chrysomelid defoliation. Defoliation scores (1=high defoliation, 4=low defoliation) were highly genetically positively correlated with initial tree size and growth parameters (increment in diameter), suggesting that reduced defoliation caused faster growth or that faster growing trees were less susceptible to defoliation. Thus, selection for growth should effectively also select for resistance to or tolerance of herbivory, particularly in trials that are subjected to leaf beetle defoliation.

Further investigations found no relationship between defoliation of *E. regnans* and phenology of shoot growth in spring, but the more resistant families produced a significantly lower proportion of new leaves that were red. Curiously, the proportion of red foliage was also negatively correlated with oviposition and subsequent defoliation levels later in the season, when the colour differences were no longer evident. This suggests that leaf colour is an indicator of other chemical properties related to attraction of egg-laying beetles (Raymond, 1998).

Another study that compared *E. regnans* families with low and high susceptibility to herbivory found a trend of lower survival of larval *P. bimaculata* on less susceptible families but no differences in growth parameters. Chemical analysis of the foliage found low susceptibility families had higher levels of nitrogen and phosphorus but there were no relationships between defoliation and content of terpenes or formylated phloro-glucinolins (Patterson et al., 1996). However, Henery et al. (2008a) found no relationships between defoliation and foliar levels of either nitrogen or formylated phloro-glucinolins. Although early field studies have suggested that herbivory is positively associated with nitrogen levels in soil and foliage (e.g. Landsberg and Wylie, 1983; Landsberg and Gillieson, 1995), laboratory studies have found that high nitrogen levels in foliage improved larval performance but not the absolute amount eaten by *Paropsis atomaria* (Fox and Macauley 1977; Henery et al., 2008a). Sub-races of *E. globulus* from Victoria were found to be more susceptible to defoliation by another chrysomelid, *Paropsisterna agricola*, than those from Tasmania—although heritability scores for egg and

larval populations were low (Rapley et al., 2004a). Steinbauer et al. (1998) proposed that it is apparent differences in leaf toughness determined by phenology between *E. regnans* and *E. nitens*, rather than other interspecific differences in foliage, that attract oviposition by *P. bimaculata*.

Cross-breeding eucalypt species with varying resistance to insect herbivory could be used to produce hybrid plantation species with greater resistance to insect pests, although often eucalypt hybrids suffer intermediate or higher levels of insect attack (Dungey et al., 2000; Dungey and Potts, 2003; Nahrung et al., 2009). Distinct feeding and oviposition preferences by *P. agricola* and *P. bimaculata* among different eucalypt species in the field have been recorded and the reasons for these preferences could be investigated further (de Little and Madden 1975; Elek 1997). Lawrence et al. (2003) found that adults of the leaf beetle *P. agricola* chose to eat about six times the amount of adult-phase compared with juvenile-phase foliage of both *E. nitens* and *E. globulus*, and about three times the amount of *E. nitens* than *E. globulus* foliage in laboratory trials. The amount of hybrid foliage eaten in the laboratory was intermediate (F1) or at least equal to (F2) the amount of *E. nitens* eaten, although in the field there were no differences amongst amounts of parent or hybrid foliage eaten.

In the unlikely situation that only one trait conferred resistance to a range of pests, then selection could be relatively easy, depending on its genetic control. It is more likely that eucalypts deploy a range of devices to resist the wide range of pests, so that selection for resistance or susceptibility could be much more complex (Henery, 2007). Such mechanisms may include both direct and indirect defences. For example, Barbour et al. (2009) found genetic variation in the amount of decorticating bark on trunks of *E. globulus* which led to differences in the number of trunk arthropods. Of the trunk arthropod species, 44% were predators and could impact on canopy herbivore populations. It might be difficult to find traits that protect trees against damage by multiple herbivores including mammals (O'Reilly et al., 2002) without seriously compromising the selection intensity on traditional commercial traits (growth and wood properties), unless the faster growing trees are also the most resistant. The main risk could be further narrowing the genetic base, which has already been narrowed during selection for favourable wood quality and growth traits. This could increase susceptibility to other pests and diseases with effects that are moderated by different host traits, or could reduce growth rates in the absence of herbivory.

The best option would be to select the trees with the fastest growth after being subjected to uncontrolled leaf beetle attack. Selection for resistance within breeding populations is likely to provide only incremental gains that would reduce but not eliminate the need for other forms of pest management. If plantation stock are less susceptible to or more tolerant of herbivory, they could be deployed in the areas at highest risk of leaf beetle attack. If the impact of defoliation is lower, then the economic damage threshold should be higher, which should mean lower frequency of control operations. Although deployment of any different genetic stock would affect the arthropod community ecology in some way (e.g. Barbour et al., 2009), the impact should be minor when compared with insecticide use.

Apart from classical breeding and selection, genetic engineering has been used outside Australia to enhance resistance of forest trees to insect herbivores. Commercial potential for genetically engineering forest trees has been demonstrated for at least 33 species, including seven eucalypt species (van Frankenhuyzen and Beardmore, 2004). The main traits engineered have been herbicide tolerance, insecticide resistance and lignin content.

Insecticide resistance has focussed mainly on insertion of a gene from the bacterium *Bacillus thuringiensis*, which produces an insecticidal protein. Genes that express the endotoxin from *B. thuringiensis* var. *tenebrionis* (Btt) that is toxic to leaf beetles have been incorporated into one eucalypt species in the laboratory in Australia (Harcourt et al., 2000), but that program has since been discontinued.

The main obstacle to public acceptance and regulatory approval of genetic engineering is environmental concerns (van Frankenhuyzen and Beardmore, 2004). Deployment of genetically engineered eucalypts to control leaf beetles and other herbivores is not an option in Australia while there is any risk that transgenic pollen could spread the engineered genes into the native forest environment, causing unintended consequences to non-target insects. In addition, FSC specifications prohibit the use of genetically modified organisms; only conventional breeding is acceptable.

Conserving natural enemies

Conserving natural enemies of insect pests by manipulating habitat within and around crops has been widely investigated and advocated in agricultural systems (see reviews by Pickett and Bugg, 1998; Landis et al., 2000; Gurr et al., 2004; Wäckers et al., 2005; Cook et al., 2007). This approach has been investigated only relatively recently in the forestry industry (e.g. Zanuncio et al., 1998; Steinbauer et al., 2006). The extent and success of implementation is difficult to assess (Gurr and Wratten, 2002).

Natural enemies are important natural controls for paropsine leaf beetles (Simmul and de Little, 1999). There has been considerable work identifying insects that are natural enemies of *P. bimaculata* (de Little, 1982; de Little et al., 1990; Bashford, 1999), *P. agricola* (Nahrung and Murphy, 2002; Nahrung and Allen, 2004a; Rice, 2005), *P. cloelia* (Nahrung and Clarke, 2007) and *Paropsis atomaria* (Nahrung et al., 2008b; Duffy et al., 2008). Natural enemies normally kill more than 95% of eggs and larvae of these species in plantations (Elliott and de Little, 1980; de Little, 1982; de Little et al., 1990; Nahrung and Allen, 2004a). Most of these are predators that target chrysomelid eggs and young larvae. They reduce larval defoliation in the short term, and may respond quite rapidly to outbreaks to reduce the first-generation adult population and to moderate population increases over the longer term. The major insect predators of *Paropsisterna bimaculata* and *P. agricola* eggs and larvae appear to be the generalist ladybirds *Harmonia conformis* and *Cleobora mellyi* (Coleoptera: Coccinellidae), the soldier beetle *Chauliognathus lugubris* (Coleoptera: Cantharidae), spiders and an unidentified mirid (Othotylinae), with a wide range of other minor predatory insects (Elliott and de Little, 1980; de Little et al., 1990; Mensah and Madden, 1994; Shohet and Clarke, 1997; Bashford, 1999; Nahrung and Allen, 2004a). European wasps (*Vespula germanica* and *V. vulgaris*) that have recently invaded Tasmania have been recorded

preying on chrysomelid larvae (pers. comm. Chris Spencer and Karen Richards, March 2009) as they have in New Zealand (Styles, 1969).

Parasitoids are often very specific to their hosts but those that target *P. bimaculata* and *P. agricola* may also attack a range of paropsines (Simmul and de Little, 1999). However, very few parasitoid species have been recorded attacking *P. bimaculata*; egg parasitism is very low, while reports of about one-third of the larvae being parasitised by one braconid wasp and two tachinid fly species have been made (de Little, 1982; de Little et al., 1990). Parasitism rates of *P. agricola* eggs were also very low in Tasmania (2%) but were much higher in Victoria (up to 55%) (Nahrung and Murphy, 2002). Mortality of *Paropsis atomaria* eggs in northern Australia due to wasp parasitism was around 30% (Duffy et al., 2008). The braconid wasp that parasitises *Paropsisterna bimaculata* larvae also parasitises *P. agricola* larvae, and two of three tachinid parasitoids of *P. agricola* larvae also attack *P. bimaculata* (Nahrung and Allen, 2004a; Rice, 2005). Most parasitoids do not kill larvae until pupation. The exception is the tachinid *Balde striatum*, which often targets and kills young *P. agricola* larvae before they finish feeding. Pupal mortality of *P. agricola* due to parasitism was commonly about 30%, but total mortality including death of larvae due to physical damage caused by oviposition (and possibly feeding) by the parasitoid could reach 50% or even 75% (Rice, 2005). There are few reports of parasitoids on adult beetles. Selman (1989) reported adults being parasitised by a mermithid nematode that usually (but not always) kills its host, but parasitised adults are rarely recorded (Nahrung, 2004). Sexually transmitted parasitic mites have been recorded on *P. agricola* (Seeman and Nahrung, 2004) and those parasitising *Paropsis atomaria* were shown to reduce its longevity during overwintering (Nahrung and Clarke, 2007). Thus, parasitoids are probably important for moderating populations over the longer term and probably reduce the recurrence of outbreaks, rather than controlling outbreak populations within a season.

Reports of vertebrate predation of chrysomelid leaf beetles are rare. There are anecdotal reports from fishermen of trout gorging themselves on swarms of adult beetles that land on the water of inland lakes in Tasmania, so fish may moderate populations of adult beetles. It would be reasonable to assume that insectivorous birds are also significant predators of chrysomelid larvae and adults, since they can comprise over one-third of plantation eucalypt canopy insects (Elek et al., 2004). There are no published records of bird predation of chrysomelids but there have been some observations of birds preying on Tasmanian chrysomelids. Smaller birds (silveryeye, olive whistler and cuckoo species) have been observed taking chrysomelid larvae while larger corvids (forest raven and currawong species), kookaburras and magpies have been noted taking adult chrysomelids in Tasmania (pers. comm. Chris Spencer and Karen Richards, March 2009).

Many lizards and small mammals are also insectivorous so, as for birds, one would expect that leaf beetles would comprise an important food source, particularly the pupae and overwintering adult beetles under the bark, in rotting logs and leaf litter. Three lizard species and both quoll species have been recorded eating adult chrysomelids in Tasmania (pers. comm. Chris Spencer and Karen Richards, March 2009). Echidnas have also been recorded eating chrysomelids (Chris Spencer and Karen Richards, unpublished data).

Mallick et al. (1998) reported that over 80% of scats of southern brown bandicoots, which are relatively common in Tasmania, contained remains of beetle larvae and adults, including chrysomelids. In native US forests, small mammals were found to be important prey on introduced gypsy moths. The level of consumption of gypsy moth pupae in litter was found to be directly related to the population of native mice and to the crop of acorns (Elkinton et al., 1996). However, Elkinton et al. (2004) concluded that the mice were unlikely to be able to prevent outbreaks because gypsy moths were not their favourite prey. Up to 99% of gypsy moth pupal deaths in Slovakia have been attributed to vertebrate predators (Turčáni et al., 2001).

There is still a lot to be learnt about natural enemies. For example, we need to identify which predators and parasitoids in Australia have the greatest impact on pest populations throughout their life cycle, and need detailed studies of the enemies' life histories, alternative food and hosts, and how they persist over winter.

Conserving overwintering sites for natural enemies

Another method of enhancing natural enemy control could be to conserve their overwintering sites in the vicinity of plantations. Both leaf beetles and ladybirds overwinter as adult beetles. Ladybirds in particular take refuge in huge aggregations under bark and in cracks of dead trees, especially standing dead trees (Baker et al., 2003). Anecdotal reports from treefellers describe hundreds of ladybirds streaming out of felled trees; there have been other reports of large clusters of ladybirds overwintering in attics or other artificial structures. Barbour et al. (2009) found that *E. globulus* trees with rougher bark supported higher diversity arthropod communities, which would include natural enemies.

Provision of artificial overwintering sites for ladybirds has been investigated (Elek, unpublished data). Six designs of 'houses' that mimicked wood-splits, crevices and bark lifting off dead trees were built on top of 3m-high poles and tested in a young plantation in southern Tasmania. Unfortunately none of the houses attracted ladybirds; only spiders and European wasp queens used them for overwintering. Laboratory trials that tested whether ladybirds were attracted into boxes containing bark collected from overwintering trees also gave no conclusive results (Elek, unpublished data).

Further work could test whether retention of standing dead trees or trees with rough bark around the boundary of plantations, such as in streamside reserves or wildlife habitat strips, increases populations of ladybirds and reduces leaf beetle populations or damage within plantations. If the results were positive, we could increase retention of standing dead trees (stags) around plantations, provided safety risks to plantation workers were managed.

Alternative sources of food and hosts for natural enemies

Researchers worldwide, particularly in agricultural systems, are investigating the retention of alternative food and hosts for conserving natural enemies. Many insect predators may be routinely polyphagous or feed on different prey when their main prey is not available. For example, when leaf beetle eggs or larvae are not available, ladybirds have been observed feeding on psyllids on *Acacia* spp. in Tasmania (JE pers. obs.; Dean Thatchell, pers. comm.). At different stages in their life history, many natural enemies also feed on sugar sources such

as flower nectar or honeydew from sapsuckers (Wäckers et al., 2005). Parasitoids are generally more specific to their hosts than predators, but even they can have several hosts and most also depend on sources of nectar, honeydew or pollen for sustenance (Stapel et al., 1997; Baggen and Gurr, 1998; Short and Steinbauer, 2004; Winkler et al., 2009). Rice (2005) found that provision of sugar or honey significantly extended the longevity of all three parasitoids of *Paropsisterna agricola* in the laboratory, from 1 to more than 20 days. In addition, a tachinid fly that parasitises *P. agricola* larvae also parasitises larvae of the chrysomelid *Peltoschema orphana* that feeds on silver wattle, *Acacia dealbata*, during winter. Thus, silver wattles may support an important alternative host to retain the flies in plantations during winter. Therefore, Rice strongly recommended increasing plant diversity within or nearby plantations to provide alternative food sources for chrysomelid parasitoids.

Natural enemies need to be both attracted into and retained within the crop. Providing or augmenting alternative food sources may act as attractants for natural enemies as well as increasing their survival and residency time within the crop. This should increase their effectiveness at reducing pest populations, assuming the alternative food sources do not substitute for the target prey, nor compete strongly with the crop. The main research focus in agriculture has been on finding plants that would provide the best alternative food sources for natural enemies, either directly or by supporting alternative prey or hosts (e.g. Evans and Richards 1997; Evans et al., 1999; Idris and Grafius, 1995; Gurr et al., 2004; Wäckers et al., 2005; Winkler et al., 2009). There have been only a few studies in forestry that show that increasing plant diversity within or in the vicinity of eucalypt plantations also increased insect and natural enemy diversity (Zanuncio et al., 1998; Steinbauer et al., 2006). Elek and Beveridge (2000) identified several native understorey flowering plants that were attractive to major predators of *P. bimauculata*.

Several eucalypt species, such as *E. nitens*, produce manna (white sugary crystalline sap) following physical damage to green stems or leaves, including from herbivore feeding. This might be providing natural enemies with an important carbohydrate source, since flies, ants and European wasps have been observed feeding on it (J.E. pers. obs.; Steinbauer, 1995). Chrysomelid larvae have been found mired in the substance. Steinbauer (1995) speculated it might be an induced response to herbivory by the eucalypt and debilitate the pests and attract natural enemies. We need to know more about manna production, its effect on moderating defoliation, and whether the propensity to secrete it is heritable. If found to be a heritable trait inversely correlated with defoliation, it could be a useful selection trait.

There are many gaps in our knowledge of the importance of vertebrate predators for moderating leaf beetle populations, particularly outbreaks. If vertebrate predators are important, management to augment bird, lizard and small mammal populations in the landscape could enhance leaf beetle control.

The few studies on bird populations in eucalypt plantations have shown that birds were present but numbers were generally lower than in surrounding native forest in Australia (Hobbs et al., 2003; MacDonald et al., 2002), and in Brazil, where eucalypts are not native (Marsden et al., 2001). However, Loyn et al. (2007) found that insectivorous birds foraging in the canopy and tall shrubs or on the ground between trees were common in plantations in

Victoria, Australia. In regions where agriculture dominates the landscape, eucalypt plantings maintained bird populations (MacHunter et al., 2006). Eucalypt plantations provided important habitat in particular for woodland-dependent birds (Kavanagh et al., 2007). Bird populations in eucalypt plantations were directly related to plantation size, age and distance from forest remnants (Loyn et al., 2007). In particular, retention of native vegetation nearby plantations significantly increased bird numbers in the plantations (Lindenmayer and Hobbs, 2004). A good diversity of understorey plants within the plantation is probably also important for providing alternative food and shelter for birds and small mammals, as for insect natural enemies. Birds should not adversely affect arthropod natural enemy populations since many of them are unpalatable, as shown by the warning coloration of wasps, ladybirds and soldier beetles.

Native eucalypt forest is generally dominated by only a few eucalypt species but has much higher diversity of subdominant trees and understorey shrubs than plantations or agricultural land. Eucalypt plantations generally comprise only one tree species with varying amounts of herbaceous and woody understorey. The amount of understorey depends on the previous land use and the effectiveness of weed control. Plantations can have quite dense and diverse native shrubbery for the first rotation following harvesting of native forest but could become progressively less dense and diverse in later rotations if weeds are intensively controlled. On former agricultural sites the understorey is generally much less diverse and includes many non-native species. Weed control is generally better due to easier vehicular access into plantations and availability of herbicides specific for monocotyledon (grass) weed species. Jones (2001) suggests that lower plant diversity in plantations may favour pest populations that are higher and comprise different species from those in more diverse native forest habitat. Jones et al. (2002) found that autumn gum moth defoliation of young *E. globulus* was lower on shorter trees where weeds were denser; whether this was due to better natural enemy control or lower apparency of the trees to the pest was not determined. The level of weed control could influence the level of natural biocontrol, but this would need to be balanced with loss of growth due to weed competition (Wilkinson and Neilson, 1990).

Further work is needed to determine the most effective level of plant diversity that does not compromise tree growth (Hunt et al., 1999), that provides the most important food sources to the most important natural enemies, and how far these enemies will move between alternative food sources. We also need to ensure that the alternative foods do not replace the target pests as a food source. Using different silviculture regimes to move from monoculture to a mixture of plantation species could also affect natural enemy populations (see below).

Silviculture regimes to minimise impact of defoliation

Manipulation of silvicultural regimes at the stand and landscape levels has been recommended for reducing the impact of insect pests. Coyle et al. (2005) suggested that plantations with more diverse tree species might have fewer pest problems. Certain silvicultural practices can be used to increase vegetation diversity within the stand and the landscape—such as species and age composition (Brockerhoff et al., 2008). Vegetation and structural diversity should support more diverse insect fauna that would be expected to include natural enemies of plantation pests (Strauss 2001; see also ‘Conserving natural enemies’). However, while some

silvicultural management regimes may reduce pest attack, they may also reduce tree growth (Major et al., 2009).

At the stand level, eucalypt plantations generally comprise only one eucalypt species (e.g. either *E. globulus* or *E. nitens* in southern Australia) compared with Australian native forest that usually has several eucalypt species and often several non-eucalypt tree species. A meta-analysis of 119 studies worldwide (which included eucalypt leaf beetles) found lower levels of herbivory in mixed-species forests compared with single-species forests, particularly in relation to oligophagous insect pests (Jactel and Brockerhoff, 2007). Species composition appeared to be more important than species richness *per se*. Forests comprising similar classes of trees (e.g. all broadleaved) had higher levels of herbivory and higher survival of herbivores than forests comprising tree species from different classes (broadleaved and coniferous) (Riihimaki et al., 2005; Jactel and Brockerhoff, 2007). Mixed-species stands may also have the disadvantage of attracting more generalist herbivores (Koricheva et al., 2006). Leaf beetle defoliation levels were observed to be lower in native forest that incorporated high densities of silver wattle, *Acacia dealbata* (Greaves, 1966). A review of 18 trials of eucalypt plantations incorporating nitrogen-fixing species showed that in all but one trial the eucalypts had higher relative yields and the majority of trials had greater total yields compared with a monoculture (Forrester et al., 2006). However, Hunt et al. (1999) found that competition from fast-growing *Acacia* spp. weed infestation reduced the productivity of the plantation in spite of a net contribution of nitrogen into the soil. *Acacia* spp. also have their own pest problems: for example *A. dealbata* can be severely defoliated by the chrysomelid fireblight beetle, *Peltoschema orphana*, often resulting in death (Elliott, 1978). A study comparing a small Australian plantation comprising several *Eucalyptus* and *Acacia* species of different ages with a monoculture showed that parasitoid populations were higher in mixed-species and mixed-aged plantings than in the monoculture (Steinbauer et al., 2006). However, interplanting with several species of eucalypts or other tree species would complicate management for wood production, since the different species would have different growth characteristics, silviculture and harvest requirements. One method of incorporating different species would be to design the planting of the second species destined for removal in an early thinning, by which time many of the benefits of improved pest control would have been achieved.

Silvicultural regimes could be modified to reduce susceptibility of the most sensitive growth stages. For example, pruning at least 50% of the lower crown of *E. nitens* or *E. globulus* growing on good sites should not significantly impact growth (Pinkard and Beadle, 1998; Pinkard et al., 1999; Pinkard, 2003). However, pruned trees are sensitive to further loss of foliage for several months after pruning. They would suffer growth losses if insect defoliation removed another third of their upper crown, especially if both occurred during summer. Therefore, if pruning was done during winter after leaf beetles have finished feeding, it might allow sufficient time for the pruned trees to compensate physiologically before being exposed to the risk of leaf beetle defoliation in the following spring–summer (Pinkard et al., 2004).

Thinning is a recommended management tool for reducing susceptibility of trees to primary boring insect pests, such as *Sirex* wood wasp and some bark beetles, but it could have unintended effects on populations of other pests species (Hindmarch and Reid, 2001;

Neumann and Minko, 1981; Schmitz et al., 1989). The effect of thinning eucalypt plantations on leaf beetle populations has not been investigated. Although the vigour of the retained trees should be enhanced, the higher quality of their foliage might attract higher leaf beetle populations that could reduce the growth benefits of thinning.

Fertilising trees has been suggested as a management tool to reduce the growth impact of defoliation (Pinkard et al., 2006a and b; but see Herms, 2002). Increasing the nitrogen content of foliage could increase attractiveness of trees to insect defoliators since herbivores are known to prefer foliage with higher nitrogen levels (Fox and Macauley, 1977; Ohmart et al., 1987; Mattson Jr., 1980). However, nitrogen fertilisation was found to cause no increase in psyllid attack of eucalypts (Stone, 1993) and foliage of eucalypts with lower susceptibility to herbivory was found to have higher levels of nitrogen and phosphorus (Patterson et al., 1996). Fertilised trees should also be growing faster and so better able to compensate for defoliation. A study of the interactions among fertilisation, defoliation and tree growth of *E. globulus* plantation trees demonstrated that trees fertilised with nitrogen, especially pre-defoliation, showed better crown condition and net growth compared with unfertilised trees, even after incurring some defoliation (Pinkard et al., 2006a and b). Therefore, there is scope to manipulate fertiliser regimes (timing and amount of nitrogen) to increase the chances of trees compensating for defoliation, and reducing their susceptibility to economic damage.

Other silvicultural operations within plantations could also enhance natural enemy diversity. For example, it has been suggested that practices such as windrowing, mound ploughing and leaving prunings and thinnings to rot in the plantation would enhance diversity of predators such as ground-dwelling carabid beetles (Bonham et al., 2002). Similarly, presence of thinnings on the ground and retained trees with hollows should also increase bird numbers (Loyn et al., 2007). However, retention of more fuel within plantations could increase the fire risk.

At the landscape level, eucalypt plantations in Australia are generally part of a mosaic of native eucalypt forest, plantations of different ages and species (e.g. *Eucalyptus* and *Pinus* spp.) and agricultural land (mostly pasture). Coyle et al. (2005) suggested that plantations that are smaller and more scattered in the landscape might have fewer pest problems. However, a high ratio of perimeter to area, as well as the length of perimeter adjacent to native forest, could increase their susceptibility to damage by certain insect pests that favour plantation forest edges, such as gumleaf skeletoniser *Uraba lugens* (Wotherspoon and Jennings, 2009), as has been found for mammal browsing in Tasmania (Bulinski and McArthur, 2003). Smith (1999) investigated the relationship between outbreaks of *Paropsisterna bimaculata* in plantations and the proportions of surrounding vegetation types but was not able to find any direct relationships. This type of study is difficult since landscapes are so variable. Since that study, spatial analysis tools have vastly improved and both plantation estates and datasets expanded, so the topic would be worth revisiting.

The absolute size of a plantation could also affect its natural biocontrol. Tasmanian plantations vary in size from about 10 ha to over 100 ha, averaging about 50 ha. Eucalyptus weevil (*Gonipterus* sp.) eggs were attacked by wasp parasitoids at similar intensities for 200 m from the plantation–native forest edge (Elek et al., 2008). Spatial analysis could determine the size

and shape of plantations in relation to the surrounding landscape that resulted in the best levels of natural regulation; that is, fewest pest outbreaks. However, in practice, the available sites and many other operational factors often dictate size and shape of plantations.

Silvicultural regimes in the landscape can also affect the mosaic of ages of plantations. A diverse age structure of eucalypts creates a more diverse landscape with different sized trees with both juvenile and adult foliage that support different populations of herbivores and natural enemies. De little et al. (2008) has shown that paropsine chrysomelid occurrence on *E. nitens* and *E. globulus* in Tasmania increased with plantation age until trees had all changed into adult-phase foliage. Björkman et al. (2004) suggested that maintaining plantations in a mosaic of different age classes would better preserve the resident natural enemy complex when pest species are moving in from outside plantations. However, a continuum of age classes in the landscape could favour pests such as *P. agricola* (and diseases such as *Mycosphaerella* leaf disease) that specialise on juvenile foliage since the pest could disperse from plantations moving into adult-phase foliage to the younger plantations that still had juvenile foliage (Nahrung, 2004).

Much more research would be required to demonstrate the effects of different silvicultural practices and plantation configurations in the landscape on the natural management of insect pests before practical prescriptions could be developed.

Trap trees

Trap crops are one of the earliest methods used to manipulate the behaviour of pest species for monitoring purposes or to lessen the damage to the target crop, particularly in agriculture (Hokkanen, 1991; Foster and Harris, 1997). Trap crops that are more attractive than the target crop plants attract pests away from, and so protect, the target crops from damage (Hokkanen, 1991). This definition has been expanded to include the strategies for deployment of the trap plants, so that trap crops have recently been defined as stands that are ‘deployed to attract, divert, intercept, and/or retain targeted insects in order to reduce damage to the main crop’ (Shelton and Badenes-Perez, 2006). Trap crops are classified as either conventional trap crops, which are more attractive than the main crop for pest feeding and oviposition, or ‘dead-end’ trap crops, in which the pest cannot complete its development or is killed (see ‘Lethal trap trees’ below). Methods of deployment include perimeter, interplanting of the trap and main crop, sequential planting in time and ‘push–pull’ trap cropping (see below). They can also be combined with biological control or behaviour-altering chemicals (kairomones or pheromones). The major factors that determine the success of the trap cropping are the movement characteristics of the target pest, the relative attraction and the deployment strategy of the trap and crop plants (Hannunen, 2005; Shelton and Badenes-Perez, 2006).

Trap crops have been widely tested in agriculture to attract pests away from target crops (Hokkanen, 1991; Barbercheck and Warrick, 1997; Banks and Ekbom, 1999). However, there are only 10 out of 53 agricultural and forestry pest species documented for which trap cropping has been successfully deployed commercially (Shelton and Badenes-Perez, 2006). One example has been management of Colorado potato beetles in tomato crops by interplanting potato plants (Hunt and Whitfield, 1996). An infochemical pest attractant has been found to increase the efficacy of the potato trap crop (Martel et al., 2005a and b).

Trap trees have been an integral part of one of the classical biological control success stories—controlling *Sirex* wood wasps in conifer plantations (see ‘Lethal trap trees’ below). Certain native eucalypt species have been found to be more attractive for feeding and oviposition by *P. bimaculata* than the plantation species *E. nitens* and *E. globulus* (Steinbauer et al., 1998; Elek 1997 and unpublished data). *P. agricola* also has feeding preferences among eucalypt species in the field (de Little and Madden, 1975; pers. comm. V. Patel, April 2009, CRC for Forestry, Tasmania). These tree species could be grown around the perimeter or within plantations to attract beetles and reduce the numbers attacking plantations. Rows or blocks of trap tree species (*E. regnans* and *E. delegatensis*) planted within *E. nitens* plantations have been trialled in Tasmania, and found to attract higher populations of leaf beetles than the adjacent *E. nitens* (Elek, 1997). However, the slower growth and continual defoliation by leaf beetles of the unprotected trap trees, and perhaps the low proportion of trap to crop trees, meant that they did not adequately protect the *E. nitens* from defoliation (Elek, unpublished data). An economic analysis was carried out to determine the proportion of trap to crop trees that would remain economic. Wood values at harvest (NPV) were compared for coupes that had given over varying proportions of the crop to trap trees, using Farm Forestry Toolbox (Private Forests Tasmania, PO Box 180, Kings Meadow Tasmania 7249). The results suggested that more than 1% of the crop given over to trap trees would be not be economic (Elek, unpublished data). However, smaller blocks of trap trees could be useful monitoring tools, or deployed as lethal trap trees (see below).

Limitations of trap crops are that they require a lot of knowledge to identify and test them and generally they only target one of many crop pests. In addition, they have different management requirements to the main crop and may entail loss of cropping area so that they are not cost-effective relative to insecticide control (Hannunen, 2005; Shelton and Badenes-Perez, 2006).

Lethal trap trees

Lethal trap trees are a category of ‘dead-end’ trap crops (Shelton and Badenes-Perez, 2006). Lethal trap trees, in this case killed trees of the same species, have been widely used in forestry for monitoring *Sirex* wood wasps in *Pinus* spp. plantations in combination with biological control (Bedding and Akhurst, 1974; Neumann et al., 1982; Neumann and Morey, 1985; Neumann and Marks, 1990; Haugen and Underdown, 1993).

For managing eucalyptus leaf beetles, lethal trap trees could be created by treating attractive eucalypt ‘trap trees’ with systemic insecticides so that their foliage becomes toxic to the target insect pest(s). The trap trees would attract and aggregate the pest, which would then be killed when they fed on the toxic foliage. These lethal trap trees would act as a sink for the pest species so that they should not spill over or invade the adjacent crop trees for feeding or oviposition. Since the beetles would be killed, a smaller proportion of lethal compared with non-lethal trap trees should be required. The deployment of the trees in relation to the crop could also influence their effectiveness; for example, whether planted in the centre or around the edge between native forest and plantation. This is a landscape option since trap trees would need to be planted at the same time as the rest of the crop. The necessity for planting the future lethal trap trees could be based on spatial analysis of historical data to identify regions that

have more regular over-threshold populations of leaf beetles. The actual treating of the trap trees with insecticide to create toxic foliage could be based on the predicted leaf beetle populations since the insecticides can be taken up into the foliage within about a week, depending on the application method. Treated in this way they could be considered a 'control' option. The preferred methods for introducing systemic insecticide into trap trees are by stem injection or spraying the bark, since these methods would have the least impact on non-target organisms compared with soil injection or spraying the foliage. They provide more rapid uptake of insecticide into foliage than soil injection. Lethal trap trees should have negligible direct effect on natural enemies since they target only foliage-feeders.

Existing IPM programs target mainly larval rather than adult eucalyptus leaf beetle populations. However, herbivory late in the summer, such as that by the first-generation adult beetles, has the greatest growth impact (Candy et al., 1992; Elek, 1997; Candy, 1999). Lethal trap trees would provide longer term control, remaining lethal throughout the summer and autumn months to protect trees from both larval and first-generation adult feeding. They could be treated for as many years as the crop is threatened with economic damage, providing the insecticide did not affect pollinating insects. The trap tree species planted need to specifically attract the herbivore pest targeted.

Combining repellent and attractant plants: 'Push-pull' concept

Some non-host plants may be repellent to pests. Since certain eucalypt species have been found to be more attractive to *P. bimaculata* for feeding and laying eggs than the plantation species, other species might be less attractive or even repellent. There may be plant species that are repellent which could be included as understorey or groundcover. For example, a study in Tasmania found some negative relationships between numbers of *P. bimaculata* leaf beetles trapped and the density of understorey vegetation species; one explanation for this relationship could be that some understorey *Senecio*, *Zieria* and *Olearia* spp. have a repellent effect (Elek, unpublished data).

The concepts of repellent plants and trap crops have been combined in agriculture to encompass a 'push-pull' or 'stimulo-deterrent diversion' concept. This was first developed for Australian cotton more than 20 years ago (Pyke et al., 1987; Cook et al., 2007; Miller and Cowles, 1990). One non-crop repellent plant species is interplanted within the crop to repel insect pests and another trap crop is planted around the perimeter to attract them; the trap crop is preferably a 'dead-end' crop (Cook et al., 2007). Perceived advantages of a dual system are that it has at least an additive effect of the two components and may have a multiplicative effect on the pest. In addition, several different systems being active simultaneously should reduce the likelihood of resistance developing (Miller and Cowles, 1990; Cook et al., 2007). The oft-quoted example of implementation of this concept is for controlling cereal stem borers in maize in Kenya, where one species interplanted with the maize repels the borers and another species around the boundary attracts them for oviposition; the trap crop is in fact a 'dead-end' trap crop since the borers cannot complete their life cycle on it (Khan et al., 2000; Hassanali et al., 2008).

Forestry provides another other good example of using the 'push-pull' strategy. Several bark beetle pheromones have been shown to produce density-dependent responses, whereby low

concentrations attract beetles and their natural enemies while high concentrations repel. These have been employed in a ‘push–pull’ strategy to reduce attack rate by bark beetles on several native conifers (e.g. Lindgren and Borden, 1993; Amman and Lindgren, 1995; Lindgren and Miller, 2002; Miller et al., 2005a and b).

Controlling outbreaks

Management options for controlling outbreaks are reviewed under three main headings: modifying use pattern of insecticides, classical biological control and artificial attractants or repellents for pests and natural enemies.

Modifying use pattern of insecticides

Replace broad-spectrum with softer insecticides for aerial spraying

Broad-spectrum insecticides, such as pyrethroids (e.g. α -cypermethrin) or organophosphates (e.g. malathion, carbaryl), are very effective at killing all stages of insect pests but they also kill all non-target insects, including beneficial insects, and many are very toxic to aquatic fauna.

A major advantage of newer insecticides is that they are designed to target the pest insects better and generally have much less impact on non-target insects, including natural enemies. A corresponding disadvantage is that mostly they target only one and not several pests. For example, the biological insecticide containing the insecticidal toxin derived from the bacterium *Bacillus thuringiensis* var. *tenebrionis* (Bt) targets only beetle larvae that eat treated foliage, so it has little direct effect on most non-target insect fauna such as flies, wasps, moths, predatory beetles or aquatic fauna (Glare and O’Callaghan, 2000). It would also not kill any lepidopterous larvae feeding on the trees. Bt sprays were extensively used to manage Colorado potato beetle in the USA, until potato plants were genetically engineered to incorporate the Bt protein (e.g. Ferro and Gelernter, 1989; Wierenga et al., 1996; Hilbeck et al., 1998). Bt has been used to control the introduced chrysomelid elm leaf beetle larvae on street trees in California and Australia (Cranshaw et al., 1989; Thurston, 1998; Wells et al., 1994).

Aerially sprayed Bt was found to be effective at reducing young (first and second instar) larval populations of *P. bimaculata* (Elek and Beveridge, 1999; Beveridge and Elek, 2001). Laboratory trials demonstrated that it did not kill several major predators (Beveridge and Elek, 1999). However, the liquid formulation is expensive and logistically difficult to use on a large scale, which would restrict its use to high-risk areas. As a result of forest plantation use being a very small market, Bt has not been registered in Australia.

Laboratory and field trials with a product based on spinosad (derived from a soil actinomycete) indicated that it would be effective at managing *P. bimaculata* young larval populations while being softer on natural enemies at the doses required (Elek et al., 2004). Although the spinosad spray affected populations of some natural enemies such as wasps, most of the residential non-target insects were not affected. The beneficial insect populations had recovered to pre-spray levels within one month after spraying with the spinosad insecticide, compared with two months after spraying with α -cypermethrin (Elek et al., 2004). Two spinosad products have been registered for controlling leaf beetles on eucalypt

plantations in Australia and one of these (Entrust[®]) has been accredited by BFA (Biological Farmers Association) for use on Australian Certified Organic (ACO) products.

The botanical insecticides pyrethrum (a.i. pyrethrin) and neem (a.i. azadirachtin) are being used commercially in agriculture (Isman, 2006). However, organic pyrethrins are less potent and less persistent than synthetic pyrethroids (Casida, 1980), and were found to be ineffective at protecting potato crops from the Colorado potato beetle (Kühne et al., 2008). Preliminary trials found them to be phytotoxic to eucalypt foliage so their efficacy against eucalyptus leaf beetles was not pursued further (HJ Elliott, unpublished data). Neem has been found to be toxic to leaf beetle larvae and was suggested as a potential tool in leaf beetle IPM (O'Brien et al., 2003). However, some preliminary trials found that it was also toxic also to some major predators, so no further work was carried out (Elek, unpublished data). Similarly, preliminary evaluations found fipronil to be too broad-spectrum to be evaluated further as an alternative to α -cypermethrin for aerial spraying (Elek, unpublished data).

Another group of chemicals, the neonicotinoids (including imidacloprid and clothianidin), are potential alternative insecticides but are not expected to be registered for general aerial application in forestry due to their relative broad-spectrum insecticidal activity (see below 'Different application technologies and formulations').

Insect growth regulators are new-generation insecticides that target the physiological processes controlling larval growth of insects (Retnakaran et al., 1985). However, juvenile hormone analogues or moult inhibitors, such as methoprene, and the chitin-synthesis inhibitors are not considered suitable for a forest environment because they are also toxic to all crustaceans (Wright, 1976; Cohen, 1987; Wright and Retnakaran, 1987), which would include endangered giant freshwater crayfish and yabbies.

A disadvantage of most softer insecticides is that they only target larvae, and often only young stages, and do not control the adult pests directly (e.g. products based on Btt and spinosad). This provides only a narrow window of effectiveness and means that it is difficult to time sprays for optimal efficacy (see also below 'Time insecticide sprays'). In addition, leaf beetles continue to lay egg batches every one to two weeks throughout the summer so that several different age classes of larvae may overlap in the one area (de Little, 1983; Nahrung and Allen, 2004a; Howlett et al., 2000).

Biological insecticides are acceptable by all forest certification standards. This includes Bt, pyrethrum and neem insecticides and should also include spinosad-based insecticides. Criteria for acceptability of non-biological insecticides are currently not well defined in AFS, while the criteria used by FSC puts some of the 'softer' insecticides such as imidacloprid in doubt. Currently, acceptability of insecticides is based on the hazards of their active ingredients rather than the risk of the formulated product after application in the field (Govender, 2002; Tomkins, 2004). For example, since method of application is not taken into account, imidacloprid is not acceptable under most standards although it would have a much lower environmental impact if applied by stem injection or bark spray compared with being aerially sprayed.

Time insecticide sprays to minimise impact on natural enemies

The IPM system to manage Tasmanian leaf beetles aims to time application of insecticides onto the second instar larvae, to allow the majority of the predation that occurs on the eggs and first instar of *P. bimaculata* and *P. agricola* to occur (see ‘Conserving natural enemies’) (Elliott et al., 1992). There is currently only limited data on the life history phenology of the major natural enemies. Nahrung and Allen (2004a) recorded that most egg and larval predators and larval parasitoids of *P. agricola* were present from October to March but they did not record stage (e.g. adult or larval ladybirds) or density. Many of these natural enemies also attack *P. bimaculata*. Soldier beetles were present from October until March but they peaked in November to December (Shohet and Clarke, 1997). Only the adult soldier beetles prey on leaf beetles; after feeding on leaf beetle eggs in the spring, soldier beetles lay their eggs in the soil and their larvae feed there for the rest of the year (Shohet and Clarke, 1997). Bashford (1999) recorded that ladybird adult numbers peaked during October to December, when they fed on leaf beetle eggs and laid their own eggs. These hatched to predatory larvae that fed on leaf beetle larvae later in the summer. The next generation of ladybirds was observed feeding on psyllids on *Acacia* spp. An egg parasitoid of leaf beetles was only detected in two of three seasons at one site in December and January; however, it could have been present earlier in the season at very low levels before its population built up to detectable levels (Nahrung and Allen, 2004a).

It is impossible to time insecticide treatments to avoid all periods when natural enemies are active. Killing larvae will also indirectly affect their parasitoids. Since peak soldier beetle and ladybird adult populations, and their egg-laying, both occur during early summer (November–December), avoiding spraying with broad-spectrum insecticides during this period would help conserve them (Bashford, 1999; Shohet and Clarke, 1997). However, since most over-threshold populations of *P. bimaculata* first appear in early summer (Forestry Tasmania unpublished data), using softer insecticides would reduce the impact of control on natural enemies. A combination of timing and using softer insecticides could greatly reduce the negative impact of pest control on natural enemies.

Different application technologies and formulations

All aerial spraying is carried out under strict regulations and guidelines to reduce the risk of off-site contamination from spray drift. Using different application methods and formulations may target the pests better, and further reduce the risk to non-target natural enemies and off-site contamination from spray drift.

Spot or strip treatment of foliage or soil can better target the application where there is a high risk of contamination of sensitive areas, such as buffers adjoining water courses or residences. This method reduces the risk of aerial spray drift and the amount of pesticide applied per hectare would be reduced. This option is only viable for seedlings or very young trees.

Soil applications of granular, tablet or liquid formulations of systemic insecticides that are taken up by tree roots have been shown to protect trees for one or more years against some pests (Nicholas et al., 2003; Cowles et al., 2006; Collett and McBeath, 2007), although high dose rates may suppress seedling growth (Hurley and Patel, 2003). Systemic uptake should

target herbivores and sapsuckers (and possibly also stem-borers) almost exclusively and have little direct impact on other guilds of insects in the foliage. However, there could be non-target effects on local litter and soil fauna and an increased risk of water contamination if the pesticide had a high mobility in the soil. Bees and native wasps could be at risk if the insecticide translocated into nectar or pollen of target eucalypts or understory species. The risk to honey bees could be managed by moving commercial hives. However, the risk to native bees and wasps would require that eucalypts were only treated before they flower and that flowering understory species were removed before application. Tablets added into the planting hole that release imidacloprid pesticide and fertiliser slowly into the soil have been registered to protect eucalypt seedlings in Australia (Initiator[®]). A liquid formulation of clothianidin (Shield[®]) has also been registered for soil injection in eucalypt plantations in Australia. The cost-effectiveness of all slow-release treatments will be directly related to the length of time the insecticide persists at toxic levels.

Trunk applications of systemic insecticides have been used successfully to protect eucalypts and other trees from sapsucking, defoliating and boring insects (Hand et al., 1995; Elek, 1997; Helson et al., 2001; Young 2002) but were found to be less effective than soil injections against hemlock woolly aphids (Cowles et al., 2006). Other less-intrusive methods for uptake of systemic insecticides pesticide via the green bark may have potential, such as application of insecticides formulated as paints, bandages or patches (Kwong and Field, 1994; McCullough et al., 2006; Elek, unpublished data). Trunk application, whether applied to the bark or by injection, should target any herbivore or wood-borer not just the target pest species. Compared with soil application, there would be less risk of water and soil contamination, but the risk of contamination of nectar, pollen and leaf litter would be similar. Trunk application, particularly by injection, would be very labour-intensive if all trees were treated. It would be more cost-effective if the insecticide protected the trees for the whole of one or more insect seasons and if only a small proportion of trees needed treatment (see ‘Lethal trap trees’ above). The fate of the insecticide in the leaf litter needs to be investigated.

Biological control

Biological control is to reduce the population of a pest using natural enemies or diseases until it is below a level that causes unacceptable damage.

Classical biological control

The term ‘classical biological control’ is being used here to describe the control of pests that have been introduced from another ecosystem, by agents that are usually introduced from the original ecosystem of the pest. Classical biological control is being widely used to control pests introduced from Australia into eucalypt plantations overseas by introducing natural enemies from Australia. For example, parasitic wasps have been introduced to control paropsine pests in New Zealand (Bain and Kay, 1989; Bain et al., 1984; Edwards and Suckling, 1980; Murphy, 2008) and *Gonipterus* spp. eucalypt weevils in South Africa, Spain and California (Tooke, 1953; Cordero Rivera et al., 1999; Hanks et al., 2000). Introduced parasitic wasps and nematodes from Europe have also been very successful at keeping the introduced *Sirex* wood wasp at very low levels in Australian *Pinus radiata* plantations (Haugen et al., 1990; Neumann and Marks, 1990). However, since eucalyptus leaf beetles are

native insects in Australia and already have a suite of natural enemies, classical biological control is not appropriate. The main methods of biological control that could be used to control leaf beetle populations in eucalypt plantations in Australia would be to enhance levels of natural disease or natural enemy populations within plantations in response to outbreaks.

Enhance natural diseases

Natural diseases could be cultured and released into plantations to enhance natural biocontrol of pest populations that are over the damage threshold. Disease spores could be ground-sprayed or aerially sprayed or autodispersed using attract-and-kill traps. Lacey and Goettel (1995) and Lacey et al. (2001) have reviewed the current and future use of insect pathogens as biocontrol agents and concluded that, to be more widely used, formulations need to be improved so they are more effective and easier to use. In addition, the value of the environmental benefits of biological control must increase so that the comparative cost differential decreases. Apart from spraying *Bacillus thuringiensis* (Bt) (see 'Modifying use pattern of insecticides'), there have been only three success stories reported in the use of diseases to control insect pests: the palm rhinoceros beetle virus, *Sirex* wood wasp nematodes and gypsy moth fungus (Lacey et al., 2001).

A baculovirus from Malaysia has been very effective at controlling infestations of rhinoceros beetle, *Oryctes rhinoceros*, in coconut palm plantations in the South Pacific. Its success is attributed to its long-term persistence, virulence to larvae and multiplication in the gut followed by autodispersal by adult beetles, which are sterilised but not killed by the infection (Bedford, 1986; Huger, 2005).

Methods of controlling *Sirex* wood wasps infecting radiata pine plantations with entomopathogenic nematodes were developed in Australia more than 30 years ago and are still used operationally worldwide in combination with trap trees (see 'Trap trees') (Haugen et al., 1990; Neumann and Marks, 1990). Entomopathogenic nematodes gave good control of all stages of Colorado potato beetle in laboratory trials but produced variable results in the field (Stewart et al., 1998).

Epizootics (animal epidemics) caused by the fungus *Entomophaga maimaiga* have controlled outbreaks of gypsy moth in North America. The fungus has spread both naturally and by introduction of resting spores (Hajek et al., 1996; Reardon and Hajek, 1998; Nealis et al., 1999; Villedieu and van Frankenhuisen 2004). A nucleopolyhedral virus (Gypcheck[®]) that is specific to gypsy moth is aerially sprayed to control gypsy moths in sensitive areas and to 'slow the spread' of the moths (Cunningham et al., 1991, 1993 and 1997; Reardon et al., 1996).

Applications of the entomopathogen fungi *Beauveria bassiana* and *Metarhizium* spp. have been investigated for controlling outbreaks of numerous insect pests. Control of Colorado potato beetle with *B. bassiana* produced the same potato yields as the insecticide treatments (Hajek et al., 1987). The Asian longhorned beetle has been infected in the field with *Beauveria* spp. and *Metarhizium* spp. using spray and impregnated fibre bands on tree trunks, reducing its longevity and oviposition rate on the trees (Dubois et al., 2004a and b; Hajek et al., 2006). *Metarhizium* spp. have been extensively tested and delivered aerially for

controlling plague locusts in Australia (Hunter et al., 2001), and have also been investigated for controlling termite colonies (Milner et al., 1996 and 1998). Infective diseases could also be autodispersed using attractant traps (Vickers et al., 2004; see also 'Attract-and-kill traps').

Strains of the entomopathogenic fungi *B. bassiana*, *M. anisopliae* and *Entomophthora* sp. are known to occur naturally and kill leaf beetles in Tasmania, particularly when adult beetles are overwintering (Madden et al., 1999; Nahrung and Allen, 2004a). Cultured *B. bassiana* and *Metarhizium* spp. strains have both been found to be effective at killing *P. bimaculata* and *P. agricola* larvae and adults in the laboratory. However, they were very slow acting at Tasmanian temperatures, were dependent on high moisture levels and also killed some major predators, so it was considered that the fungi would not be suitable for controlling leaf beetle pests (Madden et al., 1999). The strains were not tested for effectiveness against pupae or overwintering adults. While application of entomopathogens at this stage of the life cycle would reduce population levels, they would not be effective at managing outbreaks.

No bacterial or viral diseases of chrysomelids have been identified. Other parasites such as mermithid worms occur occasionally but affect relatively low proportions of the populations (Selman, 1989; Simmul and de Little, 1999).

Rear and release natural enemies

Enhancing natural enemy populations could be used to control outbreaks of leaf beetles. The use of ladybirds for biological control has been widely used against agricultural and orchard pests (e.g. Obrycki and Kring, 1998; Dixon et al., 1997; Wyss, et al., 1999). The Tasmanian ladybird, *Cleobora mellyi*, has been reared and egg-wasp parasitoids have been introduced into New Zealand as part of classical biological control for the Australian paropsid beetle, *Paropsis charybdis* (Bain et al., 1984; Bain, 1989; Murphy, 2008).

A study on releasing large numbers of ladybirds to augment the natural populations for controlling Tasmanian leaf beetles concluded that releasing ladybirds would be feasible but would probably not be economically viable on a large scale because of the large numbers required and their short-term impact (Baker et al., 2003). *Paropsisterna bimaculata* egg and larval population decreased significantly immediately after release of the ladybirds. However, the numbers of ladybirds on trees surrounding the release site decreased steadily until they reached background levels within seven days after release.

There have been studies on the effects of releasing other species of ladybirds on native ladybird populations, which suggest that populations quickly return to the background level supported by the available resources; in some cases though the introduced species supplanted the native species (Elliott et al., 1996). This could happen with laboratory-reared strains of the same species, which would not be desirable for maintaining genetic diversity.

Artificial attractants or repellents for pests or natural enemies

Any artificial attractants or repellents would have limited lifespans and incur some cost, so they would most likely only be deployed to control outbreaks. The two main types of artificial attractants or repellents are food or infochemicals.

Artificial food attractants

Artificial food attractants could be a substitute for infochemicals or natural food for attracting and retaining natural enemies within plantations. Trials in Tasmania using artificial food (sucrose) feeding stations attracted some beneficial insects but the overwhelming response was to attract and feed European wasps (Mensah and Madden, 1994). Mensah has since developed Envirofeast[®] that is designed to attract and sustain beneficial insects to manage cotton budworm (Mensah, 1996, 1997). The wettable powder is now registered by Bayer CropScience for spraying onto cotton crops in NSW and Queensland. Other products (Aminofeed[®], Aminofeed UV[®] (Agrichem), Predfeed[®], Bugpro[®], Denkavit[®] and the chemical L-tryptophan) have since been developed as attractants for natural enemies. Nufarm has developed Mobait[®] as a feeding stimulant for defoliating pests to increase the efficacy of insecticides that are based on *Bacillus thuringiensis* and spinosad. It aims to attract caterpillars out of cabbage hearts and cotton buds so they eat more treated foliage. A sprayable product is currently being developed for the cotton industry (pers. comm. Alice Del Soccoro, Univ. New England, NSW, June 2009, and see 'Attract-and-kill traps'). An artificial protein is routinely used in traps for orchard pests (see below).

Further work might be justified to test the effectiveness of some of these commercial products for attracting natural enemies of eucalyptus leaf beetles, and to test whether they assist in reducing the pest populations.

Repellents

None of the numerous artificial repellents that have been developed against flying insects have been tested against insect herbivores, although many products have been tested for repelling mammal browsers (e.g. Miller et al., 2008). Forest trees that are less attractive to pests might produce repellent factors worth exploiting. These plant-derived chemicals fall into the category of 'infochemicals'.

Infochemicals

Infochemicals are chemicals that modify behaviours of pests and/or natural enemies, which can be harnessed for insect pest management (Shea, 1995; Foster and Harris, 1997). They can be released by any life stage of the target insect, from their frass, by chemicals emitted from the host plant on which the target insect feeds, or by the natural enemies themselves.

A considerable effort worldwide is being devoted to researching infochemicals attractive to natural enemies (e.g. Vet and Dicke, 1992; Pickett et al., 1997; Meiners et al., 1997 and 2005; Wei et al., 2008). This could become very complex when several pests with different natural enemies are feeding on the same plant or when natural enemies are polyphagous.

Infochemicals can be general for many natural enemies or specific to one. For example, green leaf volatiles such as ethanol are released by many plants when they are damaged and can be used by both pest and natural enemies to detect their hosts (e.g. Elliott et al., 1983; Whitman and Eller, 1990). Some of the plant-defence chemicals have been identified, and natural enemies can be attracted by treating plants with artificial versions of these chemicals (e.g. Birkett et al., 2000; Ozawa et al., 2008). By contrast, many infochemicals are specific for one host and predator or parasitoid (e.g. Sullivan et al., 2000). Aldrich and Cantelo (1999)

used pheromones from a natural enemy to attract more natural enemies into the crop to control Colorado potato beetles.

Infochemicals can be used to manipulate the behaviour of the target pest species, either to repel it from the crop or attract it to a trap crop or traps (see ‘Trap trees’ and ‘Attract-and-kill traps’). Compared to lepidopterans, there has been very little infochemical work on coleopterans, particularly chrysomelids. Most coleopteran work has concentrated on agricultural pests (e.g. Foster and Harris, 1997; Loughrin et al., 1996). Plant compounds from a range of host and non-host plants have been found to elicit attractant and antifeedant behaviour by the mustard leaf beetle, which has potential for biocontrol of weeds (Kühnle and Muller, 2009). Plant-derived antifeedant chemicals have been shown to reduce colonisation and oviposition by chrysomelid Colorado potato beetle (Yamasaki et al., 1989; Murray et al., 1995; Gols et al., 1996). There is evidence that the Colorado potato beetle releases volatile aggregation and sex pheromones (Dickens, 2006; Edwards and Seabrook 1997), and an artificial host volatile attractant has been developed for it (Dickens, 2000; Martel et al., 2005a and b).

Although not strictly infochemicals, commercially available chemicals that induce resistance to diseases (or pests) have many advantages over conventional chemicals used for disease control, such as better safety profiles (Leadbeater and Staub, 2007). If chemicals can be found in eucalypts that induce resistance to herbivores, they could be developed to help trees resist attacks only when necessary (Eyles et al., 2001). However, there is no conclusive evidence that herbivory on eucalypts induces production of defensive infochemicals (Henery et al., 2008b), although an upward trend in foliar tannins following defoliation suggests that they may have been induced (Rapley et al., 2008).

In forestry, most research has concentrated on identifying plant- and insect-based infochemicals for wood borers and bark beetles, some of which have been deployed for monitoring and control of infestations (Elliott et al., 1983; Ross and Daterman, 1994; Borden, 1997; Deglow and Borden, 1998; Campbell and Borden, 2006; Fettig et al., 2009 and see ‘Trap trees’). For foliar feeders, the sex pheromone of the gum leaf skeletoniser *Uraba lugens* has been identified and used for monitoring introduced populations in New Zealand (Suckling et al., 2005). Sex pheromone components of autumn gum moth, *Mnesampela privata*, have been identified but not fully evaluated in the field (Steinbauer et al., 2004a; Östrand et al., 2007; Walker et al., in press). Chemicals have been identified on leaf surfaces that allow autumn gum moths to discriminate between leaf types (Steinbauer et al., 2004b). Leaf surface chemicals that vary with tree clones also stimulate feeding by chrysomelid cottonwood leaf beetles (Lin et al., 1998a, b; Coyle et al., 2003).

Slow-release formulations of infochemicals have been developed that can be aerially sprayed. Pine beetle antiaggregation pheromone encapsulated in small beads reduced attack of mountain pine beetle (Shea et al., 1992), and sex pheromones microencapsulated into a slow-release product disrupted mating and reduced infestation by pine moths for up to 75 days (Gillette et al., 2006).

Work is in progress to investigate the role of infochemicals for modifying the behaviour of eucalyptus leaf beetles. Nahrung et al. (2009) have identified several chemicals in *Corymbia* hybrids that could be tested for their effect on the behaviour of *Paropsis atomaria*. A whole-plant chemical has been isolated from a *Eucalyptus* species that elicited an attraction response in *Paropsis atomaria* (pers. comm., Simon Lawson). Field trials using sticky traps showed that both sexes of *Paropsisterna agricola* were more attracted to shoots with feeding beetles of either sex than to undamaged shoots; it was not determined whether the beetles were attracted by infochemicals from the beetles, the damaged foliage or by some other factor (Nahrung and Allen, 2004b). Similar traps enclosing shoots (with no beetles) on adjacent pairs of different eucalypt species caught almost seven times as many *P. bimaculata* beetles on *E. regnans* than on *E. nitens* trees (Monjaret and Elek, unpublished data). The highly aggregated and very mobile *P. bimaculata* populations suggest that aggregation pheromones may also be produced (Clarke et al., 1997). *P. bimaculata* showed stronger antennal responses to whole-foliage volatiles from *E. regnans* compared with *E. nitens*, and prospective chemicals have been identified from the foliage and beetles for testing for their effects on the behaviour of the beetles (Quarrell et al., 2009).

Some of these infochemicals could also be effective at attracting natural enemies.

A combination of aggregation and sex pheromones, in addition to plant-derived infochemicals, has been used for managing the behaviour of Colorado potato beetle (Dickens, 2006; Edwards and Seabrook, 1997).

The use of infochemicals would seem to be an ideal pest management option since they are generally effective at very low concentrations, are target-specific, and should have low impact on non-target species as well as a small chemical footprint in the environment. However, for various reasons, including cost and the fact that they only target one pest, the use of infochemicals for insect pest management is rare (Vet and Dicke, 1992). They have their biggest uptake when a crop is threatened predominantly by one pest species, which is frequently the case for exotic pests such as introduced bark and boring beetles. More frequently, infochemicals have been used as lures in traps (see below) and as monitoring tools (Gage et al., 1990; Lyytikäinen-Saarenmaa et al., 1999; Suckling et al., 2005).

Attract-and-kill traps

This technique combines several methods. It relies on an attractant (food source or infochemical) to attract pests to a source that administers a lethal substance (disease or chemical). Traditional traps with lures are used for monitoring pest populations, but the addition of a lethal substance (a physical sticker, disease or insecticide) transforms them into a pest-control measure (Foster and Harris, 1997). The specificity of the attractant will largely determine the specificity of the control measure, and hence how much direct impact it has on non-target insects. The attraction could be a natural plant such as a trap tree, or an artificial attractant applied to foliage or deployed in a trap. The attractant could be an infochemical or a food. Traps can also include a visual attractant to increase their effectiveness (Piñero et al., 2009). They could be combined with a ‘push–pull’ strategy (refer to ‘Trap trees’).

Attract-and-kill traps have been used for a long time to eradicate or control fruit pests in the orchard industry (e.g. Steiner et al., 1965; Hossain et al., 2008). Attractant traps have been tested for proof-of-concept and are now being tested for their efficacy at spreading entomopathogenic fungi to control orchard pests in the field (Hartfield et al., 2001; Vickers et al., 2004). A specially designed trap that attracts and kills sheep blowflies, Lucitrap[®], has been shown to be effective at reducing blowfly populations (Urech et al., 2009). Traps using a combination of visual and chemical cues have been developed for the forest industry to trap bark beetles (French et al., 1977; Lindgren, 1983; Lindgren et al., 1988; Bjorklund et al., 2005; Campbell and Borden, 2006).

A commercial spray-on product, Magnet[®], has been registered in Australia to control noctuid moths on cotton, beans and sweet corn crops (<http://www.agbiotech.com.au/magnet.php>). It combines attractant plant volatiles with a feeding stimulant, to which an insecticide is added to create an attract-and-kill product, sprayed onto 1.4% of the crop (pers. comm., Alice Del Socorro, University of New England).

Cues that attract or repel eucalypt leaf beetles would need to be identified for use in traps. These could be infochemicals (see 'Artificial attractants') or visual cues (Stenberg and Ericson, 2007). It has been determined that a certain wavelength of yellow is the best colour for attracting *P. bimaculata* to sticky traps (Clarke et al., 1997; J. Madden, unpublished data,) and leaf colour has been related to herbivory levels (Raymond, 1998).

Deployment of attract-and-kill traps with artificial attractants could be more efficient than lethal trap trees because plantation area need not be taken up with trap trees. The method could also be used in response to outbreaks rather than as a prophylactic in predicted 'hot spot' areas. Attract-and-kill traps should be acceptable as organic control measures under all certification regulations. However, the cost of deploying enough traps to manage defoliation could be more costly than aerial spraying with a broad-spectrum insecticide.

Evaluation of management options

Methods

An earlier version of the preceding review of the potential options for improving the management of Tasmanian chrysomelid leaf beetles was circulated to nine Australian colleagues. In addition to the authors, three of the colleagues were employed in the forest industry in Tasmania, with their major responsibilities being to research and manage protection of eucalypt plantations from pests and diseases. Four other colleagues were employed in Australian research institutions and had been advisors to the forest industry on pest management issues. Two colleagues had just completed their doctoral studies on ecology and biological control of Tasmanian leaf beetle species.

Workshops were held with those colleagues to discuss the review and evaluate the main management options. The baseline against which the options were evaluated was the most widely used method of controlling pest outbreaks: aerial spraying of over-threshold populations with the broad-spectrum insecticide α -cypermethrin. Each participant scored each

of seventeen management options independently from poor or unacceptable (0) to excellent (5) for five criteria: their effectiveness in reducing larval and adult leaf beetle populations below levels that would be economically damaging; expected feasibility or ease of deployment for operational use; impact on the biotic and abiotic environment; social acceptability; and perceived cost (see Table 1).

All colleagues had experience of the forest industry, with expertise to evaluate effectiveness, feasibility and the environmental implications of potential methods of managing leaf beetles, so these criteria were given a weighting of 1 for ranking. The five employed in the forest industry had good understanding of silvicultural management and the costs associated with pest management. However, none were experts in economics or social sciences, so cost and social impacts were rated as they were perceived from their experience of the forest industry. Accordingly, for ranking, these criteria were given a weighting of 0.5. The scores from all participants for the seventeen main options under five criteria were then tallied and summarised by tabulation. The options were ranked overall as well as grouped and ranked separately under 'landscape' or 'control' options, since both preventative and reactive options could be employed in practice.

Results

The baseline management 'control' option, aerial spraying with a broad-spectrum insecticide, was scored highly for effectiveness, feasibility and cost but poorly for environmental and social impacts. This resulted in fifth ranking for 'control' options and tenth over all options (Table 1).

It is notable that five of the six highest-ranking options were 'landscape' options. They all were scored highly for their feasibility, and their environmental and social benefits, but mostly received relatively low scores for effectiveness. The highest-ranking 'landscape' option, that also ranked most highly overall, was tree improvement to lift the general level of resistance or tolerance to leaf beetle attacks in plantations. Its high social and environmental scores assumed that no genetic engineering would be used, and high feasibility also assumed that trees resistant to, or tolerant of, leaf beetle defoliation could be selected and propagated by conventional tree improvement methods. The 'landscape' option ranked second, and equal second overall, was retaining dead trees as overwintering sites for natural enemies because it was scored very highly for feasibility and environmental benefits and could be implemented at little or no cost. It was scored lower on social benefits due to the hazard created by retained standing dead trees, but this could be managed by only retaining those not considered dangerous. The 'landscape' option ranked third (fourth overall) was conserving natural enemies by providing them with alternative food and hosts. Although expected to be less effective than resistant trees, it was considered to be quite feasible, as well as very environmentally and socially beneficial. Silvicultural management was ranked fourth in 'landscape' options (fifth overall), since this was seen as socially and environmentally acceptable but the panel was not confident of its effectiveness and feasibility. The lethal trap trees option was ranked below silvicultural management because of lower social and environmental benefits, since the use of insecticide still poses low risks of non-target contamination, although much lower than the risks posed by aerial spraying. Trap trees and

repellent plants were ranked lowest in ‘landscape’ options since, although they were scored highly for social and environmental benefits, they were expected to be not very effective and very costly, assuming that they would take up plantation area.

The highest-ranking ‘control’ option, and the only ‘control’ option in the top six overall, was attract-and-kill traps. It was scored highly for expected feasibility as well as social and environmental benefits, since the traps should pose virtually no direct environmental risk to non-target species, including natural enemies. However, they were expected to be costly to deploy, based on the costs of other pheromone-based traps. Ranked second in ‘control’ options, but much lower than attract-and-kill traps at equal seventh overall, were the biological control options of rearing and releasing natural enemies, and applying artificial repellents or antifeedants. They were scored highly for social and environmental benefits, assuming that only native species would be released and that the chemicals used to attract, repel or induce resistance to defoliators would be identified. Both options were considered very costly. Repellents were considered to be more effective than the natural enemies and diseases but a little less environmentally and socially acceptable, since they would probably require aerial spraying. The effectiveness of enhancing natural diseases was considered low, based on current knowledge of entomopathogenic fungi that are relatively broad-spectrum and slow acting in a cool-temperate climate. Classical biological control was ranked last of all options since it was expected to be costly and not very feasible, as well as socially and environmentally unacceptable, assuming the release of non-native control agents that would have an unacceptable impact on the biota in the native forest.

Aerial spraying of softer insecticides was scored slightly higher than the baseline broad-spectrum insecticide, since it would be more costly but was seen to be more socially and environmentally beneficial because softer insecticides would help conserve natural enemies in an IPM program. Different non-aerial methods of application could include ground spraying if site conditions were suitable, but in Tasmania would mainly include application of insecticide to the soil or trunk for individual trees. This option was ranked equal to the baseline of aerial spraying, since it was scored very high for effectiveness and relatively high for social and environmental benefits, but could still pose low risks of insecticide contamination of water and non-target animals. However, targeting individual trees would be very costly. Modifying the timing of current insecticide applications rated poorly since broad-acre spraying with a broad-spectrum product still had low environmental and social benefits.

Comparing scores for the individual criteria reveals that none of the alternative options would be as effective or feasible, and most would not be as low cost, as the baseline (Table 1). However, all but one would have better environmental and social benefits. The two ‘landscape’ options considered to be the most effective (scoring 2.5 or above) were tree improvement and lethal trap trees. The two ‘control’ options that received the highest scores for effectiveness were artificial repellents or antifeedants and different methods of applying insecticides (such as stem injection). Softer insecticides and attract-and-kill traps received the next highest scores. Of these options considered reasonably effective, both the ‘landscape’ options and three of the four ‘control’ options were also considered to be reasonably feasible: attract-and-kill traps, softer insecticides and different methods of applying insecticides. All the

'landscape' options received high scores for environmental and social benefits. The same three 'control' options that were considered reasonably effective and feasible also had good environmental benefits. However, only two of these 'control' options also had good social acceptability scores: attract-and-kill traps and different methods of applying insecticides. When cost is considered, the two 'landscape' options of tree improvement and lethal trap trees received reasonable scores, but only the 'control' option of softer insecticides was scored above the median.

Discussion

The heavy dependence on one method of protecting eucalypt plantations from economically damaging defoliation from outbreaks of leaf beetles is a high business risk when that method has issues of social acceptability. It is a much sounder business strategy to spread the risk, and have a range of management options available. In addition, alternative management methods are sought that would be more socially and environmentally acceptable, with a smaller chemical footprint. The review and evaluation of potential management options was carried out to identify alternative methods that could be incorporated into IPM of leaf beetles in the future. Since many of these options are not yet available for managing eucalyptus leaf beetles in Tasmania or Australia, the evaluations also suggest future directions for research to develop the most promising options.

The choice of experts to evaluate the management options summarised in this review was based on their expertise in and understanding of the role of leaf beetles in eucalypt plantations and the forest environment in Tasmania. All had worked for some years on forest pest management research issues in Tasmania, as members of Cooperative Research Centres for forestry research.

It is very difficult if not impossible to rank objectively the importance of the five criteria. Options that are not very effective would generally not be expected to be worthwhile, but if they are low cost and easy to implement, then they might still be worthwhile if they contribute to a reduction in frequency of outbreaks. Criteria could also have different rankings of importance in different situations. For example, FSC standards currently restrict the use of non-biological insecticides and require social acceptability. Thus, the weightings of the five criteria do not reflect their relative importance, but rather the level of expertise of the scientists who evaluated the management options. The scientists' main expertise was in evaluating the effectiveness, feasibility (ease of deployment in the field) and environmental impacts of the options, so these scores were considered the most reliable. Social and cost implications are no less important, but the expertise of the scientists in evaluating the options against these criteria was considered less robust, so these criteria were given half the weighting.

There was general agreement among the experts that there would not be a single magic bullet for managing leaf beetles, but that a combination of options would be most effective. Zalucki et al. (2009) have concluded that future IPM needs to be at a landscape level to be sustainable in the long term. The greatest value of 'landscape' options would be in reducing the frequency of outbreaks. Thus, future IPM of chrysomelid pests could include a

combination of ‘landscape’ options to reduce the frequency of pest outbreaks, with ‘control’ options deployed only if outbreaks occurred.

Of all the ‘landscape’ options, tree improvement to develop plantation trees that are more resistant to leaf beetle defoliation was considered the most promising, since it was scored well for all criteria. This option should be socially and environmentally acceptable as long as only conventional selection and breeding methods are employed. The main risk of tree improvement could be through further loss of genetic variability, which could increase susceptibility to other pests and diseases. Selection for resistance within breeding populations may provide only incremental gains that would reduce but not eliminate the need for other forms of pest management. Nahrung et al. (2009) have identified several chemical traits in *Corymbia* hybrids that could be used for selection for resistance to *Paropsis atomaria*. Existing tree improvement programs in Forestry Tasmania are screening *E. nitens* and *E. globulus* trees for resistance to browsing mammals, and *E. globulus* for *Mycosphaerella* leaf disease (pers. comm., Dean Williams).

A high research priority would be to screen existing tree breeding trials and seed orchards of *E. nitens* and *E. globulus* in the presence of leaf beetle populations to determine the extent of variation in defoliation levels within and between tree populations, the degree of heritability and the stability of response. If susceptibility or resistance to defoliation is found to be a stable and strongly heritable trait, the genetic correlations with growth properties and traits conferring resistance to browsing mammals and *Mycosphaerella* leaf disease will need to be determined. The fastest method of developing trees with low susceptibility could be to use conventional tree improvement, either to select out the most susceptible lines, or to select for the fastest growing trees following defoliation by leaf beetles, as suggested by Raymond (1998). Selecting for growth after defoliation does not depend on the mechanism of ‘resistance’ but selects for the desirable end point—growth rate. In the shorter term, screening existing nursery stock, and deploying stock with the highest levels of resistance in plantation areas with the highest risk of leaf beetle attack, should speed up the process of increasing genetic resistance in plantations. Discussions are underway between entomologists and tree breeders concerning the most efficient methods of screening seed orchards and tree breeding trials to determine when leaf beetle attack occurs, and assessing the level of damage. Several tree breeding trials are only just moving from juvenile to adult-phase foliage. It may also be necessary to establish new trials in areas at high risk of leaf beetle attack (pers. comm. Dean Williams).

The lethal trap tree option was second overall for effectiveness among the ‘landscape’ options and had relatively consistent scores for all criteria because it would mainly target the pest species attracted to the trap trees. It was also considered by the experts to be socially acceptable. However, the need to use insecticides to create toxic foliage could lead to a reduction in social acceptability, despite an application method that would use less insecticide and have very low risk of off-site movement. The time (and therefore cost) taken to treat the trees may not have been taken into account adequately. Lethal trap trees were expected to be much more effective and less costly than untreated trap trees, since they should not take up as much plantation area. During evaluation of the options, the experts considered that the lethal trap tree option should be pursued in the short term, when they could be deployed in high-risk

areas as a ‘control’ option to achieve a similar effect to, and help evaluate the feasibility and effectiveness of, the highest-rating ‘control’ option of attract-and-kill traps (see below).

Therefore, another high priority for research was developing lethal trap trees. Previous field trials with trap trees in Tasmanian plantations found that the slower growth and continual defoliation of unprotected trap trees stunted their growth, so that they were ineffective at protecting the surrounding plantation (Elek, unpublished data). These trials suggested that trap trees need to be protected from the impact of defoliation to remain attractive and have any continuous effect. Protecting them with systemic stem injection would transform them into lethal trap trees. Lethal trap trees research by Forestry Tasmania and the CRC for Forestry to date has determined the dose of the systemic insecticide imidacloprid that is lethal to *P. bimaculata*, and developed a method for creating this level of toxin in foliage of lethal trap trees (Elek et al., 2007, 2008). We have shown that the lethal trap trees retain their specific attractiveness to the target beetle even after being treated, in spite of the imidacloprid in the foliage exerting an antifeedant action. The treated trees remain toxic to the target beetles throughout the summer season (Elek et al., 2008, 2009). The extent of protection conferred by lethal trap trees on the surrounding *E. nitens* plantations remains to be determined.

The benefits of the various ‘landscape’ options would be expected to be at least additive. This means that, even if none were as effective as any one ‘control’ option, several options could add up to have a significant effect on reducing the frequency of pest outbreaks. Conserving overwintering sites by retaining dead trees, although expected to have only a small effect on pest populations, ranked second in ‘landscape’ options because it had very good environmental benefits and should be relatively easy and low cost to implement. Standing dead trees are known to be important habitat trees for overwintering by ladybirds, one of the major natural enemies of leaf beetles (Baker et al., 2003). This option rated lower on social benefits due to its perceived safety hazard to plantation workers. However, this could be managed by retaining only trees assessed as not dangerous. Therefore, this option might be worthwhile pursuing even if it contributes only a small degree to the reduction in frequency of outbreaks. This strategy could be deployed immediately, requiring only a management protocol for implementation.

Enhancing natural enemy populations by increasing plant diversity ranked third in the ‘landscape’ options because it received good scores for most criteria. Although not expected to have a big effect on moderating pest populations, it should add to any other landscape options being deployed. For this reason, the experts concluded that the benefits of providing alternative food and hosts were worth investigating further. All work to date on the effects on the pest populations of increasing plant diversity within and nearby plantations should be evaluated. As described in the review section of this paper, there is currently a lot of research effort evaluating the benefits of enhancing natural enemy populations in agricultural systems, as well as some in eucalypt plantations in other parts of Australia and overseas (Zanuncio et al., 1998; Jones et al., 2002; Steinbauer et al., 2006). One recent study on Tasmanian leaf beetle impacts has found that defoliation is more severe at high altitudes in Tasmania (Wardlaw, 2010), which could be a reflection of a different natural enemy community at high altitudes. Another study in progress is investigating the relationships

between leaf beetle populations and the surrounding landscape variables (pers. comm., Sophie Edgar).

Silvicultural management was ranked fourth within ‘landscape’ options, and would also add to the effects of other ‘landscape’ options deployed. Managing pruning or fertilising regimes would be more cost-effective if they were shown to have benefits in moderating impacts from leaf beetle outbreaks, as well as compensating for growth losses after an outbreak had occurred. Pinkard et al. (2006a, b) have shown that fertilising could be used to help trees recover from an uncontrolled defoliation event. This strategy could also be deployed immediately, as soon as management guidelines were developed. After this strategy has been operating for some time, data could be collected to evaluate its effectiveness at enhancing the growth of plantations.

Amongst the ‘control’ options for controlling outbreaks of leaf beetles when they occur, attract-and-kill traps was the highest ranking option, second overall to the ‘landscape’ option of tree improvement. However, attract-and-kill traps would be costly so they may only be cost-effective to deploy in high-risk and high-value sites. The effectiveness of attract-and-kill traps could be enhanced if combined with repellents in a ‘push–pull’ strategy. Another potential benefit of attractant traps is that they could be used to auto-disseminate diseases into the population, rather than just kill the beetles. This is a long-term option since the relatively high scores for feasibility and effectiveness were based on the assumption that an effective and pest-specific chemical attractant could be identified and developed for the major pest species.

Thus, attract-and-kill traps are another high priority option for research. A preliminary study at the CRC for Forestry, Tasmania, has identified several promising chemicals from a trap tree species and adult beetles that could affect the behaviour of adult *Paropsisterna bimaculata* (Quarrell et al., 2009). Considerable further work is required to test the response of the adult beetles to these and other candidate chemicals, whether attractants or repellents, and identify the most effective combinations of infochemicals for managing both *P. bimaculata* and *P. agricola*. If traps were to be used to disperse diseases, this would require more knowledge of pest-specific diseases and dispersal by the pest.

In terms of effectiveness, different application methods for insecticides rated highest for the ‘control’ options. This option also rated above the median for most other criteria except cost. It was expected to be costly because the main alternative method requires treating individual trees by stem injection, applying insecticide to the bark or to the soil around the trees. Thus, it targets the plantation trees and pests very well but is very labour intensive. Similarly, softer insecticides ranked relatively well for all criteria including effectiveness, except for social acceptability, because of the aerial spraying. Softer insecticides are less effective than broad-spectrum insecticides at managing pests because they are generally not effective on adult or later larval stages. Therefore they have a narrow window of efficacy, so it is more difficult to time applications to target the sensitive life stages. They are also considerably more expensive than broad-spectrum insecticides. This option is available to be implemented immediately using the biological spinosad-based insecticides already registered for use in eucalypt plantations in Australia. A spinosad-based granular formulation is registered for use by organic farmers.

All the 'landscape' options and the non-insecticidal 'control' options are acceptable by all forest certification standards, provided genetic engineering is not used to produce resistant trees and no exotic species are introduced. Insecticidal options are acceptable currently only if the insecticide active ingredients are biological or deemed acceptable by derogation, since formulation and application methods are not considered. However, there is pressure to develop alternative methods of rating the risk of pesticides that take into account formulation and application method, so that only the amount that enters the environment is assessed for risk. This could mean that insecticides not normally acceptable would be approved if they were applied, for example, by stem injection.

The future IPM for managing leaf beetles in Tasmania could include a range of the options reviewed and evaluated. 'Landscape' options could include deploying genetic stock that are least susceptible to damage by leaf beetles in areas at highest risk of damaging populations, retaining dead trees that do not pose an occupational hazard near plantations, and retaining or planting appropriate plant species near plantations to attract and retain natural enemies. Trap trees could be planted, or native species attractive to the pest species could be identified, surrounding plantations deemed to be at high risk of damaging leaf beetle populations, ready for conversion into lethal trap trees if required. Silvicultural management could maintain a matrix of different plantation species and ages in the landscape to prevent build-up of beetle populations, and pruning could be timed to avoid the period of main threat. If, despite establishment of these 'landscape' options, pest outbreaks occur that are predicted to cause economic loss of growth, then attract-and-kill traps could be deployed, perhaps in combination with spraying repellents on the plantation in a push-pull program. As a last resort or the lowest cost option, plantations could be aerially sprayed with a soft insecticide that does not kill the natural enemies. If all these options fail to prevent damaging defoliation, plantations could be fertilised to help them recover lost growth.

In summary, this evaluation of alternative options for management of leaf beetles in Tasmania has highlighted the best potential options for future IPM and, since many of these options are not yet available for deployment in eucalypt plantations, future research priorities. A high priority should be the development of plantation stock that is more resistant to, or tolerant of, leaf beetle defoliation. This would largely be delivered by ensuring assessments are done following naturally occurring outbreaks of leaf beetles in existing genetics trials. While tree improvement was ranked most highly overall, the critical need is for alternative control options. Attract-and-kill technology was identified as the most promising new control option to manage outbreaks when they occur, and lethal trap trees were identified as the pathway for developing that option. They should be used to determine how attract-and-kill technology modifies the behaviour of pest populations to guide deployment of attract-and-kill traps. If lethal trap trees show promise in reducing defoliation of plantations, then research should progress to investigating infochemicals that could be used to develop attract-and-kill traps. Protocols should be developed for retaining standing dead standing trees that pose no safety risk to workers near plantations, as well as for fertilising plantations that suffer severe defoliation to help them recover lost growth. The current research on effects of plant diversity on natural enemies and beetle populations should be reviewed, and the gaps identified for further research.

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Table 1

Summary table of scores for ranking 17 chrysomelid management options for five criteria, sorted under 'landscape' and 'control' options

The options were scored for five criteria: from 0 = poor or unacceptable to 5 = excellent. The baseline was ranked under the 'control options' category.

Management option	Scores							Ranks		
	Effective	Feasible	Environmental	Sub-total	Social	Cost	Sub-total	Total	Rank under each category	Overall rank
	Weight = 1				Weight = 0.5					
Baseline ('control' option)										
Broad-spectrum aerial spraying	5	5	0	10	0	4	2	12	5	10
'Landscape' options										
Tree improvement	3	4	5	12	5	3	4	16	1	1
Conserve natural enemies: overwintering sites	1	5	5	11	3.5	5	4.3	15.3	2	3
Conserve natural enemies: alternative food and hosts	2	4	5	11	5	3	4	15	3	4
Silvicultural management	2	3	5	10	5	3	4	14	4	5
Lethal trap trees	2.5	4	3.5	10	4	3	3.5	13.5	5	6
Trap trees	1	3	5	9	5	1	3	12	6	10
Repellent plants	1	2	4	7	5	2	3.5	10.5	7	13
'Control' options										
Attract-and-kill traps	3	4	5	12	5	2	3.5	15.5	1	2
Rear and release natural enemies	2	3	5	10	5	0	2.5	12.5	2	7
Artificial repellents / antifeedants	4	2	4	10	4	1	2.5	12.5	2	7
Softer insecticides	3	4	3	10	2	3	2.5	12.5	2	7
Different insecticide application methods	4	3	3	10	3	1	2	12	5	10
Artificial attractants	1	4	3	8	3	2	2.5	10.5	7	13
Enhance natural diseases	1	3	2	6	3.5	3	3.3	9.3	8	15
Modify timing of spraying	2	3	2	7	1	3	2	9	9	16
Classical biological control	2	1	0	3	1	1	1	4	10	17