CAN WE GROW CERTIFIED EUCALYPT PLANTATIONS IN SUBTROPICAL AUSTRALIA? AN INSECT PEST MANAGEMENT PERSPECTIVE*

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ABSTRACT

In the past few years several Australia forestry companies have set in place procedures for certification in sustainable forest management (Forest Stewardship Council and Australian Forestry Standard). Eucalypt plantation forestry in sub-tropical New South Wales and Queensland is substantially different from that in temperate southern Australia, with currently the majority of plantations grown for long-rotation sawlogs, and a range of tree species different from that planted for pulp in southern Australia. Also, the major insect pests in this region are multivoltine and active for much of the year, due to the warmer climate and the short milder winters, compared to shorter periods of activity of larvae of any one species of mostly univoltine insects in temperate Australia. Insect pest management strategies currently used in Australia include tree improvement, improved site-species matching, and chemical control, mostly using an integrated pest management approach. Monitoring is essential for correct timing of insecticide application but, due to limited resources, forestry companies in Australia struggle to monitor effectively for multiple insect pests over extended periods of insect activity. Because of the relative immaturity of the plantation industry in subtropical

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Australia, and the sensitivity over the use of chemical insecticides by Government forestry organisations (the major growers), little research has been conducted on establishing integrated pest management strategies. In contrast, such strategies, including regular monitoring and chemical control, have been developed in temperate Australia. There are regional issues for cost-effective management of insect pests in relation to certification, including targeted use of slow-release systemic insecticides and future development of insect-active pheromones, kairomones, and synomones. There are many areas that require further research before forest companies in subtropical Australia will be able to sustain forest certification over the long term.

Keywords: forest certification; eucalypt plantations; subtropical Australia; insect pests.

INTRODUCTION

Forest certification schemes have been developed in the past decade due to increasing public concerns over the sustainable management of the world's forests. Sustainable forest management (SFM) requires that forests are managed in an environmentally appropriate, socially beneficial, and economically viable manner, and meet the needs of the present without compromising the needs of future generations (Washburn & Miller 2003; Holvoet & Muys 2004). Forests certification schemes set guidelines and standards that forest managers can follow to achieve the goals of sustainable forest management. There are over 130 forest certification schemes (Holvoet & Muys 2004), with the more widely known being the Forest Stewardship Council (FSC), the International Standards Organisation standard 14001 (ISO 14001), the Sustainable Forestry Initiative (SFI), and schemes under the Programme for the Endorsement of Forest Certification (PEFC, formerly the Pan European Forest Certification) including the Australian Forestry Standard (AFS). The perceived benefits of forest certification are access to premium markets for timber products, recognition and credibility of sustainable forest management, and improved forest management (Kajiwara & Malnick 2000; Wilson *et al.* 2001; Hartsfield & Ostermeier 2003).

Over 50 million ha of forest and plantation are certified under the Forest Stewardship Council (FSC 2004a), over 110 million ha under the Sustainable Forestry Initiative (Wallinger 2003), and over 100 million ha under the Programme for the Endorsement of Forest Certification (2005). The majority of forests covered are native forests, with commercial plantations being only a small proportion of the area certified. In Australia, several private forestry companies have eucalypt plantations (provisionally) certified under the Forest Stewardship Council, including Hancock Victorian Plantations, Timbercorp Forestry, Integrated Tree Cropping, and the Albany Plantations Forestry Company (Forest Stewardship Council 2005), while WA Plantation Resources, Gunns Limited, and the State-owned Forestry Tasmania have eucalypt plantations certified under the Australian Forestry Standard (National

Association of Forest Industries 2005). These plantations are all in temperate Australia (Western Australia, Victoria, and Tasmania) and mostly *Eucalyptus globulus* Labill., with a smaller proportion of *E. nitens* (Deane & Maiden) Maiden. State-owned and private forestry agencies in subtropical Australia are aiming to achieve certification (Australian Forestry Standard, International Standards Organisation 14001, or Forest Stewardship Council) over the next few years, with the Queensland Department of Primary Industries Forestry recently (provisionally) certified (Australian Forestry Standard).

The majority of certified eucalypt plantations in temperate Australia consist of a single species and are grown for short-rotation pulp. In contrast, eucalypt plantations in subtropical Australia are based on several different species, with currently approx. 60% grown for long-rotation timber products and the remainder for pulp. Due to the different climates in these "regions", the plantations experience different insect pest and weed problems, with north-east New South Wales and south-east Queensland experiencing generally longer periods of weed growth and longer activity of larvae of individual insect pest species than south-east and south-west Australia. Also, due to the relative immaturity of the plantation industry in subtropical Australia and the sensitivity over the use of chemical insecticides by Government forestry organisations, little research has been conducted on establishing optimum pest management strategies. This potentially has adverse consequences for plantation managers in subtropical Australia, in that it may affect their ability to obtain forest certification. The various issues relating to insect pest management in eucalypt plantations in subtropical Australia and certification requirements, specifically those outlined in Forest Stewardship Council and Australian Forestry Standard Criteria, are discussed in this paper.

FOREST CERTIFICATION CRITERIA RELEVANT TO INSECT PEST MANAGEMENT IN EUCALYPT PLANTATIONS

The following are forest certification criteria from the Forest Stewardship Council (2002, 2004b) and Australian Forestry Standard (2003) relevant to insect pest management in plantations:

- Forest Stewardship Council Criterion 6.6: "Management systems shall promote the development and adoption of environmentally friendly non-chemical methods of pest management and strive to avoid the use of chemical pesticides".
- FSC Criterion 10.7: "Measures shall be taken to prevent and minimise outbreaks of pests, diseases, fire and invasive plant productions. Integrated Pest Management (IPM) shall form an essential part of the management plan, with primary reliance on prevention and biological control methods rather than chemical pesticides and fertilisers. Plantation management shall take every

effort to move away from chemical pesticides and fertilisers, including their use in nurseries".

- Australian Forestry Standard Criterion 5.1 Identify damage agents: "Ensure that forest managers are cognisant of the relevant and potential damage agents, are able to identify such agents in the field and are able to assess and prioritise the impact in relation to prevention/control measures".
- AFS Criterion 5.2 Maintain health: "Ensure that forest managers take appropriate measures to lessen the impact of damage agents".
- AFS Criterion 5.5 Chemical use: "Reduce the reliance on the use of chemicals consistent with availability of practical and cost effective alternatives". Further, "The use of fertilisers is an accepted practice in the cycle of plantation management".

Radosevich *et al.* (2000) were commissioned to review the Forest Stewardship Council criteria relating to chemical use and provide detailed criteria — that are "scientifically defensible" — to identify chemicals that are prohibited, unacceptable, marginally acceptable, or acceptable for use in Forest Stewardship Council-certified forests. Several authors have argued that some of the criteria proposed by Radosevich *et al.* (2000) lack scientific justification (e.g., Mihajlovich 2001; Lautenschlager 2001; Govender 2002; Tomkins 2004; Elek & Govender 2004). However, at present the Forest Stewardship Council uses these criteria to identify chemical pesticides that are prohibited in certified forests (Forest Stewardship Council 2002). The policy on chemical pesticides has recently been reviewed and updated (Pesticide Action Network 2005).

Categories of prohibited pesticides under the Forest Stewardship Council are those listed under World Health Organisation Type 1A and 1B, chlorinated hydrocarbons, and "pesticides that are persistent, toxic or whose derivatives remain biologically active and accumulate in the food chain beyond their intended use" (Forest Stewardship Council 2004b). Chemicals registered for use against insect pests in eucalypt plantations in subtropical Australia are shown in Table 1, indicating their classification under the Forest Stewardship Council. Like the Forest Stewardship Council, the Australian Forestry Standard promotes the reduction of chemical use in certified forests; however, it provides no clear guidelines on what chemicals can and cannot be used. Australian Forestry Standard certification appears to implicitly recognise the Australian regulatory system for pesticides.

Within both schemes there is a requirement for forest health surveillance and monitoring to ensure early detection of insect outbreaks, although this is stated more explicitly in the Australian Forestry Standard. Knowledge of the impact of insect pests, control options, and action thresholds for control, as well as systems to monitor and detect such thresholds, is implicit in both the Forest Stewardship

TABLE 1–Insect pests in eucalypt plantations in subtropical eastern Australia, chemicals registered for their control (Australian Pesticide and Veterinary Medicines Authority 2005) and Forest Stewardship Council (FSC) status (based on Radosevich *et al.* 2000)

Pest	Tree species	Registered chemical	FSC status
Common and damaging			
Christmas beetles (*Anoplognathus* spp.)	*E. dunnii, E. grandis, C. citriodora* ssp. *variegata*	Dimethoate	Unacceptable
Chrysomelid leaf beetles (*Chrysophtharta* spp., *Paropsis* spp.)	*E. dunnii, E. grandis, E. cloeziana, E. pilularis, C. citriodora* ssp. *variegata*	Dimethoate Spinosad (larvae only) Alpha-cypermethrin *B. t. t* (Novodor®)	Unacceptable Acceptable Unacceptable Acceptable
Psyllids (*Creiis lituratus, Cardiaspina* spp.)	*E. dunnii, E. grandis*	Dimethoate	Unacceptable
Swarming scarabs (*Automolus vulgaris*)	*C. citriodora* ssp. *variegata*, *E. cloeziana, E. grandis* × *E. camaldulensis, E. dunnii*	Dimethoate	Unacceptable
Rare			
Eucalypt sawflies (*Perga* spp., *Pergagrapta* spp.)	*E. pilularis, E. grandis, C. citriodora* ssp. *variegata*	Dimethoate	Unacceptable
Red shouldered leaf beetles (*Monolepta australis*)	*E. pilularis*	Dimethoate	Unacceptable
Eucalypt weevils (*Gonipterus scutellatus, Oxyops* sp.)	*E. dunnii*	Dimethoate Alpha-cypermethrin	Unacceptable Unacceptable
Spring beetles (*Liparetrus* spp.)	*C. citriodora* ssp. *variegata, E. cloeziana*	Dimethoate Alpha-cypermethrin	Unacceptable Unacceptable
Autumn gum moth (*Mnesempela privata*)	*E. globulus* (temperate species)	Tebufenozide Alpha-cypermethrin	Marginal Unacceptable
African black beetle (*Heteronchyus arator*)	*E. dunnii*	Dimethoate	Unacceptable

Council and the Australian Forestry Standard to reduce chemical usage. Both certification schemes promote Integrated Pest Management (IPM), which embraces all these concepts as well as knowledge of acceptable control strategies that reduce the impact on non-target organisms.

EUCALYPT PLANTATION FORESTRY IN SUBTROPICAL AUSTRALIA

Eucalypt plantation forestry in subtropical NSW and Queensland (Fig. 1) differs significantly from that in south-east and south-west Australia. The majority of young plantations in subtropical Australia (35 000 ha) are grown for long-rotation sawlogs, with *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson subsp. *variegata*, *E. dunnii* Maiden, *E. pilularis* Smith, *E. cloeziana* Maiden, and *E. grandis* Maiden the major species. These species are endemic to subtropical Australia, although they may not necessarily be planted within their native range. These plantations are managed by Government forestry agencies. The private forestry companies in subtropical Australia are growing eucalypt plantations mostly for short-rotation pulp, mostly using *E. dunnii, E. grandis*, and *E. grandis* × *E. camaldulensis* Dehnh. hybrids, and these companies manage increasing numbers of plantations, especially in the last 5 years (currently 25 000 ha).

In contrast, in temperate Australia the majority of plantations are grown for short-rotation pulp, with *E. globulus* making up over 75% of eucalypt plantations (Wood *et al.* 2001) and the majority of new plantings in the past decade.

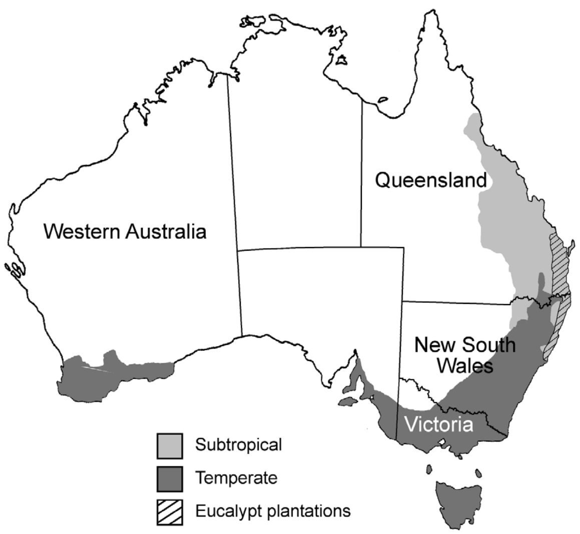

FIG. 1–Map of Australia showing subtropical and temperate climatic zones and region of eucalypt plantations in subtropical south-east Queensland and north-east NSW.

Furthermore, although plantations were established in the 1960s and 1970s in Queensland and NSW, plantation forestry in its current context is in its infancy in subtropical Australia, with large-scale establishment beginning only in the mid-1990s. The eucalypt plantation industry in south-east Australia is well established, with over 25 years of research on silviculture, tree improvement, and insect pest management. The industry in Western Australia is similar to that in subtropical Australia, with large-scale planting (of *E. globulus*) beginning a decade ago and less than 10 years of research into pest management. In all regions most planting is now on ex-agricultural land, not ex-forested land.

Plantations in subtropical eastern Australia experience a typically summer-rainfall climate, with warm humid summers and short mild winters (Bureau of Meteorology 2005). The growing season can be up to 10 months of the year. In contrast, plantations in south-east and south-west Australia experience a winter-rainfall temperate climate, with less warm weather and, importantly, a longer colder winter (Bureau of Meteorology 2005). Thus, tree growth in subtropical Australia contrasts with that in temperate Australia, and this may affect the biology of insect pests and their impact on trees.

INSECT PESTS IN EUCALYPT PLANTATIONS IN SUBTROPICAL AUSTRALIA

Damage by four “types” of insect pests can impact on eucalypt plantations.

(1) Defoliation of seedlings and saplings by herbivorous insects, such as swarming scarabs (*Automolus* spp. and *Liparetrus* spp.). These insects can cause mortality of seedlings and young saplings, and damage can result in increased costs of establishment. These insects are generally not a problem in subtropical Australia.

(2) Defoliation of established trees by leaf-chewing insects, such as chrysomelid leaf beetles and Christmas beetles. Generally, defoliating insects do not significantly impact on growth of established trees unless defoliation is greater than 50% (Abbott *et al.* 1993; Candy *et al.* 1992; Elliott *et al.* 1992), which is rarely observed in subtropical Australia (Carnegie 2000; Lawson & Ivory 2000). Also, severe defoliation is mostly restricted to younger age-classes (pre-canopy closure), and this impact will be less in a long-rotation crop than in a short-rotation crop. The longer growing season of trees in subtropical Australia may also compensate for the lost growth caused by defoliation, compared to that experienced in temperate Australia.

(3) Damage and defoliation of established trees by sap-sucking insects, such as *Creiis lituratus*. This form of damage can significantly impact on trees, resulting in top-death and tree mortality (e.g., Carnegie & Angel 2005), and it is thus an issue for both short- and long-rotation crops.

(4) Damage from stem borers, such as longicorns (*Phorocantha* spp.) and giant wood moth (*Endoxyla cinerea*). These are the most significant insect pests for a range of tree species in eucalypt plantations in subtropical Australia (Carnegie 2000; Lawson & Ivory 2000) and can impact on trees in both short- and long-rotation crops.

The suite of insect pests in eucalypt plantations in subtropical Australia has been identified from almost a decade of intensive surveys (Carnegie 2000, 2002; Lawson & Ivory 2000; Carnegie, Waterson, Cant & Price 2004; McDonald & Lawson 2004), as well as work prior to this (e.g., Stone 1993; Wylie & Peters 1993; Elliott *et al.* 1998). These are all indigenous pests. Chrysomelid leaf beetles are the most common foliar insect pests. *Paropsis atomaria* can cause significant defoliation on *E. cloeziana* and *E. pilularis* in south-east Queensland and occasionally to *E. cloeziana* in north-east NSW, and more recently has been observed causing significant defoliation on *C. citriodora* subsp. *variegata* in both states. *Chrysophtharta cloelia* is common on *E. dunnii* and *E. grandis* in subtropical Australia and is the most damaging species on *E. dunnii* in north-east NSW. Christmas beetles (*Anoplognathus* spp.) are common and damaging on several hosts, with *A. porosus* and *A. boisduvali* damaging in south-east Queensland and *A. porosus* and *A. chloropyrus* the most damaging in north-east NSW, especially to *E. dunnii.* Swarming scarabs (*Automolus* spp.) have caused significant defoliation on several occasions in south-east Queensland but rarely in north-east NSW. Eucalypt sawfly larvae (*Pergagrapta* spp. and *Perga* spp.), and leaf-blister sawfly larvae (*Phylacteophaga frogattii*), have caused severe defoliation on only a few occasions. *Cardiaspina* psyllids are common on *E. grandis* and have caused severe defoliation on many occasions in north-east NSW.

Stem-boring insects, such as *Phorocantha* spp. and *Endoxyla cinerea,* are the most significant pests in terms of potential lost production, especially in plantations established for sawlogs, and potentially also in those established for pulp production. Stem borers can cause structural damage to stems, mostly in trees more than 3 years old. This damage may allow decay fungi to develop in stems, and cockatoos feeding on larvae cause stem breakage. *Eucalyptus grandis* and hybrids with this species are the most susceptible species planted in subtropical Australia. Current management strategies rely on site-species matching to minimise the tree stress that is thought to be associated with increased levels of borer attack. Conventional management methods such as insecticide application are ineffective against these pests so research is under way to develop pheromone lures for *E. cinerea* and kairomone attractants for *Phoracantha* spp. that can be used in monitoring and control strategies for these pests.

Several new and emerging insect pests have been identified from forest health surveys in recent years. The most significant of these is the psyllid *Creiis lituratus,* which has become the most significant foliar pest of *E. dunnii* in subtropical Australia (Carnegie & Angel 2005). Severe damage, especially in plantations on low-quality sites, can result in almost complete defoliation and tree death. During outbreaks in 2003, over 450 ha were severely damaged, with up to 350 ha eventually deemed unsalvageable. *Creiis lituratus* was not known as a significant pest, or from plantations, prior to 1998. Eriophyid mites (*Rhombacus* sp.) have emerged as a new threat in *Corymbia citriodora* subsp. *variegata* plantations, especially in south-east Queensland, causing significant damage and growth loss (McDonald & Lawson 2004). They have also been observed causing significant damage in north-east NSW, but to a limited extent.

The "groups" of insect pests in eucalypt plantations in temperate Australia and subtropical Australia are generally similar, although in most cases the species are different. The main difference, however, between insect pests in these two climatic zones is their life cycles. Due to shorter periods of warm weather, and longer colder winters, insect pests in eucalypt plantations in temperate Australia are generally univoltine and often active and damaging for only a few months of the year. For example, larval populations of *Chrysophtharta agricola* are generally active from November to January in Tasmania and peak in December (Ramsden & Elek 1998; Nahrung & Allen 2004). A similar, univoltine life-cycle has been observed for *Ch. bimaculata* in Tasmania (de Little 1983). However, adult beetles of these species feed on leaves from November to late April/early May. These two species of leaf beetles are the most significant and damaging insect pests in young eucalypt plantations in Tasmania, causing extensive defoliation, growth loss, and tree mortality in severe cases, and require chemical control annually (Elliott *et al.* 1992; Ramsden & Elek 1998). As a consequence of their pest status, a substantial amount of research has been conducted on the biology, phenology, impact, and control of these species over the past 25 years (e.g., de Little 1983; Candy *et al.* 1992; Elliott *et al.* 1992; Ramsden & Elek 1998; Nahrung & Allen 2004).

In contrast, there has been little detailed research on chrysomelids in subtropical Australia, until recently. Early research on chrysomelids in north-east NSW reported that severe defoliation by *Chrysophtharta* sp. resulted in an average 62% reduction in height growth of 1- to 2-year-old *E. grandis* plantations (P.Carne unpubl. data). More recently, S.Lawson (unpubl. data) monitored populations of *Paropsis atomaria* in south-east Queensland and observed up to four generations per year with considerable plasticity in relation to availability of flush foliage. Beetles are active in plantations for about 8 months of the year in south-east Queensland, from late September to early May, with significant defoliation in plantings of *E. cloeziana* having been observed in late December, in February, and in late March–early April. The mild climate, especially in coastal plantings, promotes survival of late-instar larvae through the winter, supplementing the overwintering adult population. The effect of *P. atomaria* on tree growth could therefore be even greater than that reported for similar species in Tasmania because of the increased activity period and number of generations. However, the growing season for eucalypts is also longer in the subtropics, potentially allowing for a greater compensatory response than in temperate southern Australia. Research is currently investigating the natural enemy complex of *P. atomaria* in subtropical Australia.

The biology of *Creiis lituratus* in north-east NSW has also recently been studied (Angel 2005). Adult populations have at least three peaks — in late autumn-early winter, late winter, and late spring — with approximately 5 weeks between generations. The milder autumn and winter temperatures were found to be the cause of this multivoltism. Generally, warm weather is associated with more generations in psyllids, with *Cardiaspina* spp. in southern Australia having three generations while those in northern NSW have four to five (Clark & Dallwitz 1975; Campbell 1992). Also, higher temperatures result in less time between generations (e.g., Clark 1962). Lerp-forming psyllids are not considered significant pests in eucalypt plantations in temperate Australia, as the main species planted (*E. globulus* and *E. nitens*) are not highly susceptible (Collett 2001; Elliott et al. 1998).

Thus, the two most significant groups of foliar insect pests in subtropical Australia (chrysomelid leaf beetles and *Creiis lituratus*) are multivoltine, with normally three or more generations per year that are active for up to 10 months of the year. This is in contrast to temperate south-east Australia, where the main insect pests are univoltine (or opportunistically bivoltine). This has important implications for management of insect pests. More generations per year can result in more significant and prolonged tree damage from insects. More importantly, multivoltine insects require regular monitoring over a longer period to identify potential thresholds (triggers) for treatment compared to insect pests that have a limited activity (e.g., Angel 2005).

However, most regions have multiple insect pests with varying biologies, and so the length of time during which plantation managers need to be mindful of insects may not be shorter in temperate regions than in subtropical regions. For example, in Western Australia, the *Eucalyptus* weevil (*Gonipterus scutellatus*) season starts in mid August (with the peak egg-laying in mid September to early October and larval development in late September to early November), then adults of *Eucalyptus* weevil, *Chrysophtharta variicollis*, *Cadmus excrementarius*, and *Heteronyx* beetles feed on tree tops from late November to April. Autumn gum moths (*Mnesempela privata*) then feed on juvenile leaves from April to July. At present, only *Eucalyptus* weevil is regularly monitored and controlled with insecticides, if necessary, and significant research has been conducted on the biology of this species. The main reason why there is a management strategy for *Eucalyptus* weevil in Western

Australia is that private companies have prioritised the approach of minimising damage through proactive management.

INSECT PEST MANAGEMENT IN SUBTROPICAL AUSTRALIA

Current Pest Management Strategies

Current pest management in young eucalypt plantations in subtropical Australia includes forest health surveillance, tree improvement (including improved site-species matching), and limited chemical control. Both Government agencies (Forests NSW and Queensland DPI&F) have formal Forest Health Survey Units (FHSU) that conduct annual surveys of eucalypt and pine plantation estates. These surveys have identified and prioritised the main insect pests in subtropical Australia. However, with an expanding planting programme in the region, a large and disparate estate, and limited resources of the two agencies, neither Forest Health Survey Unit is able to visit all plantations, with less than 50% of the estate surveyed in most years. Experience of the Forest Health Survey Units and guidance from operational field staff help stratify and prioritise plantations to be surveyed each year. In contrast, none of the private forestry companies in subtropical Australia have a dedicated Forest Health Survey Unit or conduct regular forest health surveys of their plantations.

The majority of tree improvement trials in each state are assessed for damage from pests and diseases by members of the Forest Health Survey Unit (e.g., Carnegie, Johnson & Henson 2004; Henson *et al.* 2004; Lawson *et al.* 2004). Along with assessments of growth and form, this assists in selection of improved planting stock for future commercial employment. Spatial analysis of data collected during inventory assessments and forest health surveys can be used to assist in site-species matching, and when used with climatic and terrain data can produce hazard-rating maps (e.g., Borecky & Otvos 1999).

Compared to temperate Australia, there has been a limited amount of chemical control of insect pests in eucalypt plantations in subtropical Australia. In 2003, approx. 450 ha of *E. dunnii* were sprayed with dimethoate, both ground-based and aerial application, to control *Creiis lituratus* (Carnegie & Angel 2005). In all plantations, a follow-up spray was necessary within 2 weeks of the initial application. In several plantations a second spray regime was necessary within 2 months because of continued increases in insect numbers, most likely due to ineffective canopy coverage of larger trees and re-infestation. A limited amount of control was conducted the following year, with less than 50 ha sprayed. In 1998–99 spraying with dimethoate was necessary in two 1- to 2-year-old *E. cloeziana* plantations (~30 ha) in south-east Queensland to prevent further severe damage from *P. atomaria* (Lawson & Ivory 2000). This cautious use of insecticides is due in part to

Government sensitivities to public concerns, and perhaps is more conservative than that practised by private companies in temperate Australia.

In temperate Australia, aerial or ground-based application of chemical insecticides is used annually in eucalypt plantations to control outbreaks of insect pests. In Tasmania, up to 1000 ha/year are sprayed with alpha-cypermethrin for the control of chrysomelid leaf beetles, with control also often conducted for Autumn gum moth, *Uraba lugens,* and *Cadmus* spp. (Primary Industries Standing Committee 2002, 2003, 2004). However, many years of research into the biology of important insect pests (e.g., *Ch. bimaculata*), and their natural enemies, has resulted in an Integrated Pest Management strategy (Elliott *et al.* 1992) and a more targeted use of chemical insecticides. A better understanding of the natural enemy complex of insect pests in Tasmanian eucalypt plantations, and the use of insecticides that do not harm these natural enemies, has the potential to further reduce the reliance on broad-scale insecticides (Elek 1998; Elek & Beveridge 1999; Elek *et al.* 2003, 2004).

Similarly, in Western Australia, research on *Eucalyptus* weevil has enabled the development of an effective management strategy (M.Matsuki unpubl. data), which has reduced the area being sprayed with alpha-cypermethrin from approx. 10 000 ha/year to approx. 2500 ha/year (Primary Industries Standing Committee 2003, 2004). The management strategy revealed that too many plantations were being sprayed unnecessarily (i.e., when insect population levels would not cause unacceptable damage). Thus, this strategy has reduced the reliance on chemical insecticides and fits nicely under forest certification guidelines.

Pest Management Options Under Forest Certification

Chemical control

Both the Forest Stewardship Council and the Australian Forestry Standard require that chemical use, including insecticides, should be limited, with the Forest Stewardship Council requiring their eventual phasing out. Currently, there is a range of chemicals registered for use against insect pests in eucalypt plantations in subtropical Australia (Table 1). The systemic insecticide dimethoate (Rogor® and many generic products) is registered for a broad group of insects, including *Creiis lituratus,* chrysomelid leaf beetles, and Christmas beetles. Recent control operations for *Cr. lituratus* have used this chemical for both aerial and ground-based application (Carnegie & Angel 2005). The broad-spectrum, synthetic pyrethroid, alpha-cypermethrin (Dominex® and Fastac®) is registered for use against chrysomelid leaf beetles, *Eucalyptus* weevils, Autumn gum moth, and *Liparetrus* sp. In Western Australia, this insecticide has replaced dimethoate in aerial spraying and ground-based misting operations to control *Eucalyptus* weevils due to public concerns at the toxicity of dimethoate (Fremlin 2002). However, alpha-cypermethrin has not been used in plantations in subtropical Australia, mainly because dimethoate is more effective against the lerp-building psyllids *Cr. lituratus*. According to the criteria of Radosevich *et al.* (2000), dimethoate and alpha-cypermethrin are not acceptable under Forest Stewardship Council certification.

Imidacloprid is a systemic insecticide which targets only the insects which feed on the trees and so is less harmful to non-target insects than alpha-cypermethrin. It has been trialled for the control of a range of insect pests in eucalypt plantations, including *Chrysophtharta bimaculata* and *G. scutellatus* (J.Elek, pers. comm.) and *Heteronyx elongatus* (J.Matthiessen, pers. comm.) in south-east and south-west Australia, and *Cr. lituratus* in subtropical Australia (Angel 2005). Significant control has been observed when it is applied as a tablet in the soil at planting or a soil drench after planting. Imidacloprid is currently being registered for use in eucalypt plantations (J.McBeath, Bayer Environmental Science, Australia, pers. comm.), and under Forest Stewardship Council guidelines it is considered marginal.

Spinosad is registered for use against chrysomelid leaf beetles. A comparison of spinosad and alpha-cypermethrin in eucalypt plantations in Tasmania showed that alpha-cypermethrin was more effective in controlling both larvae and adults, and that spinosad was effective only against first and second instar larvae (Elek *et al.* 2004). However, spinosad was shown to be much more "environmentally friendly", having significantly less impact on the natural enemy complex within plantations, lower toxicity, and lower environmental persistence (Allen *et al.* 2004). Using the Radosevich *et al.* (2000) criteria, spinosad is acceptable under Forest Stewardship Council certification. Another "environmentally friendly" insecticide is the ecdysone agonist Mimic® (a..i. tebufenozide), which is specific to Lepidopteran larvae only (it is registered against Autumn gum moth), not harmful to non-target insects, non-toxic, and breaks down rapidly in the environment (Elek *et al.* 2003). It is likely to be marginally acceptable under Forest Stewardship Council certification (B.Tomkins, pers. comm.). The biotic insecticide *Bacillus thuringiensis* var. *tenebrionis* (Novodor®) is effective against chrysomelid larvae and has been trialled in eucalypt plantations in Tasmania (Elek 1998; Elek & Beveridge 1999). A similar insecticide, Dipel® (a.i. *B. thuringiensis* subsp. *kurstaki*), is registered for use against Lepidopteran larvae in forestry. Biotic insecticides are not routinely used in Australian plantations due, in part, to their specific environmental/climatic conditions necessary for effective control.

Under the Forest Stewardship Council, dimethoate is unacceptable, and it would need to be phased out of use in plantations if certification was the goal. An alternative, alpha-cypermethrin, is also unacceptable, and it is also not registered for *Cr. lituratus,* the main pest controlled in subtropical Australia. However, the guidelines on chemical use under the Australian Forestry Standard are less restrictive. So these insecticides may be acceptable under Australian Forestry

Standard certification, as long as alternatives have been assessed and shown to be less effective and more costly, and management have systems in place that reduce the reliance on insecticides, including an Integrated Pest Management strategy.

Spinosad is registered only for use against chrysomelids, which are rarely controlled in subtropical Australia. The small window of opportunity to spray, when larvae are at first to second instar, requires monitoring and knowledge of the timing of this window. This insecticide, which is acceptable under the Forest Stewardship Council, has potential for control of chrysomelid leaf beetles in subtropical Australia. However, more research is required to develop monitoring strategies to identify the window for effective insecticide application. Autumn gum moth is not a pest in subtropical Australia. Therefore, tebufenozide is not currently relevant to subtropical pest management.

The site-specific (targeted) use of the systemic insecticide imidacloprid (or similar active ingredients) in a slow-release formula may be a good option if chemical control is required to reduce economic losses in young eucalypt plantations in subtropical Australia. *Eucalyptus dunnii* grown on low-quality sites (e.g., poorly draining soils) are more likely to have higher populations of *Creiis lituratus* and sustain greater damage than those on better quality sites (Angel 2005). These trees are also less likely to recover after severe damage, resulting in tree mortality or substantial reduction in tree merchantability (Angel 2005; Carnegie & Angel 2005). If high-risk sites could be identified, then targeted use of imidacloprid could reduce population increase of *Cr. lituratus* in susceptible stands, thus negating the need for broad-scale application of chemicals (e.g., dimethoate).

However, imidacloprid is not effective against all pest groups of importance in the subtropics and may need to be targeted against specific groups such as leaf beetles and psyllids. For example, the eriophyid mite *Rhombacus* sp. is an emerging pest of *C. citriodora* ssp. *variegata* in south-east Queensland. Imidacloprid is not effective against mites (Acarina), and trials have shown that its use in a slow-release formulation is ineffective in controlling this pest (S.Lawson unpubl. data).

Surveillance and monitoring

Forest health surveillance to identify and prioritise insect pests is a requirement under the Australian Forestry Standard. The relevant damaging agents need to be identified and assessed for their impact and for possible control measures. Acceptable levels of damage, and its assessment, need to be specified. As mentioned above, the insect pests in eucalypt plantations have been identified and prioritised for their importance and impact (e.g., Carnegie 2000; Lawson & Ivory 2000). Field identification guides (e.g., Carnegie 2002), and training of operational field staff, assist dedicated Forest Health Survey Units on an ongoing basis. Assessment of tree-improvement trials, as well as annual surveys of commercial plantations, has quantified the susceptibility of plantation species to the key insect pests (e.g., Carnegie, Johnson& Henson 2004; Henson *et al.* 2004). National standards for damage thresholds for a range of insect pests (Stone, Wardlaw, Floyd, Carnegie, Wylie, & de Little 2003) and assessment of damage (Stone, Matsuki, & Carnegie 2003) have also been developed. All these are required under Forest Stewardship Council certification and so will assist plantation certification under this scheme in subtropical Australia.

To maintain forest health, the Australian Forestry Standard requires that forest managers have systems in place that reduce the impact of damaging agents. In subtropical Australia, both Government agencies have dedicated Forest Health Survey Units that conduct annual surveys of eucalypt plantations for early detection of pest outbreaks or the emergence of new pests, but private companies do not. Forest health surveys map the location, extent, and severity of damage agents. These are all requirements under Forest Stewardship Council certification. However, an Integrated Pest Management strategy and action thresholds for priority pests have not been fully developed in subtropical Australia. In contrast, an Integrated Pest Management strategy has been developed for chrysomelid leaf beetles (*Chrysophtharta bimaculata*) in eucalypt plantations in Tasmania (Elliott *et al.* 1992), which allows peak activity of the natural enemies of the pest and requires regular monitoring of egg and larval populations to identify action thresholds for insecticide treatment before significant defoliation occurs.

Optimising the timing of insecticide application by careful monitoring of insect populations is recommended under both Forest Stewardship Council and Australian Forestry Standard to help reduce the reliance on chemical use. The Integrated Pest Management strategy of Elliott *et al.* (1992) mentioned above is a good example of this. The insect pests have a univoltine life-cycle, with peaks of egg and larval activity over a short period (de Little 1983; Ramsden & Elek 1998; Nahrung & Allen 2004), and so regular monitoring can be restricted to a short window of insect activity. When egg and larval numbers reach a pre-determined threshold, then chemical intervention to reduce significant defoliation can be applied. Due to this short period of insect activity, a relatively large number of plantations can be monitored over a short time; approx. 10 000 ha are monitored in Tasmania annually to estimate insect pest numbers that may be a trigger for treatment (Primary Industries Standing Committee 2002, 2003, 2004).

Using a similar monitoring strategy, the *Eucalyptus* weevil is controlled in *E. globulus* plantations in Western Australia (M.Matsuki unpubl. data). Although *G. scutellatus* undergoes two generations per year in the south of Western Australia, larval hatchings peak in September-October following oviposition over spring. Severe defoliation occurs when large numbers of later instar larvae feed in the upper crown of trees in spring-summer. Egg-mass counts in mid September to early

October are used to predict which plantations are likely to suffer severe defoliation; a pre-determined threshold for the number of eggs per shoot is the trigger for chemical control when larvae emerge. Again, due the short period for egg monitoring, a relatively large number of plantations can be surveyed over a short time. However, even with this short period for monitoring, it is operationally difficult to visit all plantations requiring monitoring. Thus, in Tasmania and Western Australia, many plantations are visited either before or after the optimal timing for population assessments (M.Matsuki unpubl. data).

Knowledge of an insect pest's biology and population dynamics, and host development, allows for monitoring to be targeted for specific times of the year — and also for specific hosts and plantation growth stages. Quantification of growth losses and thresholds above which unacceptable losses occur allows for more efficient use of chemical insecticides. Knowledge of natural enemies, and at what stage in a pest's "outbreak" cycle they become less efficient, allows timing of insecticides to make full use of this natural enemy complex. Ongoing research on the important insect pests in subtropical Australia is aimed at developing Integrated Pest Management strategies.

The public sensitivity to the use of broad-scale chemicals in subtropical Australia, and the immaturity of the current plantation industry, have acted as a disincentive for research on establishing triggers for insecticide treatment. Recent studies have provided information on peaks in activity for *Paropsis atomaria* in subtropical Australia, and corresponding defoliation (S.Lawson unpubl. data), which will assist forest health practitioners in timing monitoring periods. However, these have not been trialled on an operational basis, in multiple plantations over an extended area and period. Also, no chemical control has been conducted to quantify action thresholds, and the natural enemy complex is not fully known. Further work is needed to determine whether this can be an operational reality in subtropical Australia.

Recent research on the biology of *Cr. lituratus* (Angel 2005; Carnegie & Angel 2005) has enabled monitoring methods to be developed for use in control operations in *E. dunnii* plantations in north-east NSW. *Creiis lituratus* has at least three population peaks per year, from early autumn to late spring, with 5 weeks between generations. As populations of *Cr. lituratus* begin to escalate, the natural enemy complex becomes less effective, and purpling of foliage is the first sign of insect damage to trees. Aerial surveys in mid-autumn and again in mid-winter were used to identify areas within plantations that had moderate populations of *Cr. lituratus*. These areas were then targeted for ground monitoring, with egg numbers, instar stage, the presence of adults, and crown damage monitored at fortnightly intervals (A.Carnegie & P.Angel unpubl. data). An action threshold was determined, based on the number of eggs per shoot, the proportion of un-hatched eggs, and crown damage severity. Spraying with dimethoate was then targeted to coincide with peaks in first to second instars. A follow-up spray was required within 2 weeks to control recently hatched instars. Fortnightly monitoring continued until insect control had been achieved (efficacy monitoring), or until population levels showed no sign of increase if no spray was done. This has been used operationally to control pests in up to 500 ha of *E. dunnii* in sub-topical Australia in recent years. However, further work is required to refine the methodology, and to potentially enhance the natural enemy complex.

Even so, due to limited resources no forestry company in Australia is able to monitor for multiple insect pests over an extended period in a large disparate estate. This poses difficulties in subtropical Australia where the main insect pests are multivoltine. Even if population peaks and action thresholds were determined for the most important insect pests, the multiple-peaks of these multivoltine insects and the large and disparate nature of the estate would stretch the resources of forestry companies in subtropical Australia.

Chemical remediation

One alternative that is being trialled in subtropical Australia to reduce the reliance on chemical insecticides is the remedial use of fertilisers and weed control after defoliation. Remedial methods that improve tree recovery may be more acceptable and cost-effective than regular monitoring and chemical control. Trials have shown that trees treated with fertiliser and weed control after severe defoliation (caused by *Cr. lituratus*) recovered lost growth within 6 months (Angel 2005). These trees reached the same height as trees that were undamaged (due to protection with imidacloprid) and had not received fertiliser (Angel 2005). In this trial, there were no differences in height between trees protected from insect damage and those where fertiliser and weed control were applied after severe damage. This method will also reduce the chances of tree mortality after severe defoliation on low-quality sites. Similarly, artificial defoliation trials in young eucalypt plantations in Tasmania have demonstrated a reduction in impact of defoliation through fertiliser application (L.Pinkard unpubl. data).

Therefore, due to the high cost of regular monitoring to determine action thresholds, it may be more cost-effective to use remedial action than insecticides. This is also likely to gain more public acceptance. Under the Forest Stewardship Council, some herbicides commonly used in eucalypt plantations and fertilisers are not permitted, and the justification for this, and its feasibility in Australian plantations, have been questioned (Tomkins 2004). However, fertiliser use may be acceptable when only one or two applications are made over a long rotation. Under the Australian Forestry Standard, fertilisers are acceptable, and are a suggested option to reduce the use of herbicides and/or insecticides. Thus, it is suggested that the above alternative to broad-scale insecticides is a viable option under forest certification in subtropical Australia.

Genetic and silvicultural methods to improve tolerance of trees to insect pest damage

Tree improvement is widely used in forestry to improve growth and yield, with selection based mostly on growth, form, and wood properties, but also on pest and disease tolerance. Tree improvement trials have already been used to select tolerant seedlots for commercial deployment in subtropical Australia. For example, provenances, families, and clones tolerant to Ramularia shoot blight, the most important disease of *C. citriodora* subsp. *variegata* in subtropical Australia, have been identified (I.Johnson & A.Carnegie unpubl. data). Provenances and clones have also been identified for tolerance to Eriophyid mites (S.Lawson unpubl. data; A,Carnegie & M.Henson unpubl. data). Tree improvement is a viable option to reduce the impact of insect pests, and is currently the main strategy used in subtropical Australia.

Several authors (e.g., Elliott *et al.* 1998; Stone 2001; Stone & Birk 2001) have suggested that silvicultural methods — such as weed control, thinning, and choosing species that are best suited to a particular site — can be used to reduce the impact of insect attack in plantations. Stress caused by drought, waterlogging, soil nutrient deficiencies, and weed competition may increase the susceptibility of trees to insect attack (Elliott & de Little 1984). *Eucalyptus camaldulensis* trees stressed by water deficit are affected more by insect damage than those with sufficient moisture because the rate of leaf consumption exceeds the rate of leaf replacement under water stress (Stone & Bacon 1995). Studies on *E. dunnii* in north-east NSW showed that weed competition and waterlogging increase the susceptibility of trees to herbivorous insects (Stone & Birk 2001). In both these studies (Stone & Bacon 1995; Stone & Birk 2001) it was suggested that "the stress-inducing factors reduced canopy growth rates and architecture so that the proportion of tissue damaged by insects increased and the tree's ability to tolerate this damage decreased" (Stone 2001). This also implies that the tree's ability to recover from this damage is reduced. Thus, by selecting planting sites for optimal tree growth, it may be possible to reduce the damage sustained by trees from insects, and also to improve their recovery after any damage. However, due to shortage of suitable land for forest plantations in subtropical Australia, and the demand for more planting, it is likely that trees will be planted on sub-optimal land in the future.

CONCLUSIONS

Some forest companies in temperate Australia that rely on chemicals to control damaging insects are now certified under either the Australian Forestry Standard or the Forest Stewardship Council. However, most of these companies have conducted research on their main insect pests and developed Integrated Pest Management strategies that help them reduce the reliance on chemical insecticides. Even so, further reductions in chemical usage (required under certification) will be problematic, and thus these companies will find it difficult to maintain certification (particularly to Forest Stewardship Council standards). The relative immaturity of the plantation industry in subtropical Australia, and the sensitivity over the use of chemical insecticides by Government forestry organisations, has resulted in little research on the control of insect pests. Recent studies have improved this situation, but more knowledge is required to develop comprehensive Integrated Pest Management strategies for the main insect pests. The financial costs to forest managers are expected to increase under forest certification (Wilson *et al.* 2001; Hartsfield & Ostermeier 2003; Kilgore & Blinn 2003), and research to develop Integrated Pest Management strategies will form part of these costs. Several insect pests currently have the potential to challenge the commercial viability of eucalypt plantations in subtropical Australia. It is suggested that within an economic environment of diminishing management resources the risk management of these plantations will require access to synthetic chemicals such as insecticides, fertilisers, and herbicides in the foreseeable future. In the long-term, the current suite of endemic insect pests are likely to be able to be managed under forest certification as long as research is conducted to develop Integrated Pest Management strategies to reduce chemical use over time. A bigger hurdle for certification may be the increased weed growth experienced in subtropical Australian plantations, with the Forest Stewardship Council restrictions on herbicide use. There are clearly challenges for those who want to maintain certification of eucalypt plantations in all regions of Australia.

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