

Biology and control of psyllids, and the possible causes for defoliation of *Eucalyptus camaldulensis* Dehnh. (river red gum) in south-eastern Australia – a review

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Summary

Psyllids are one of the most devastating insect pest groups in Australia, affecting both native forests and eucalypt plantations. They feed on a wide variety of eucalypt host species, with some psyllid species restricted to a single eucalypt host species or to a group of closely related species. Predominant amongst eucalypt species attacked by psyllids is *Eucalyptus camaldulensis* Dehnh., an important tree species for a variety of reasons including the insect and decay resistance of the timber, its role in reducing water table levels and minimising erosion along streams and rivers, its adaption to soils with significant salt content, and its importance as a habitat for native wildlife. In recent years it has become a candidate species for plantation forestry, especially in the northern irrigation areas of Victoria. This paper briefly examines the biology of psyllids, covering their identification, description and life-cycles, and providing a brief history of major psyllid outbreaks in Australia. The potential for attack, levels of defoliation and subsequent impact on tree growth and tree health are also examined. Options for control of psyllids are discussed to enable landholders and forest plantation managers to make more informed decisions on ways of dealing with outbreaks on eucalypts, particularly *E. camaldulensis*.

Introduction

Psyllids belong to the insect Order Hemiptera, Suborder Sternorrhyncha and Family Psyllidae, and are represented in Australia by some 330 variably structured species which cover a wide range of habitats. Most Australian psyllids belong to the subfamilies Spondyliaspidae and Acizzinae. The former is largely associated with eucalypts and the latter with acacias (Carver *et al.* 1991). Subfamily Spondyliaspidae consists of: (1) free-living psyllids which generally reside on the growing tips of young eucalypts such as *Eucalyptus globulus* (blue gum), *E. nitens* (shining gum) and *E. leucoxyton* (yellow gum), and (2) lerp-building psyllids which construct either soft or hard coverings (or lerps) of various designs and sizes beneath which the immature instars (nymphs) shelter and feed (Phillips 1996). Of the 10 lerp-building genera in subfamily Spondyliaspidae, species of *Cardiaspina* build the structurally most complex and diverse lerps and cause the most damage to eucalypt foliage, especially to *E. camaldulensis* (river red gum). Twenty-three species of *Cardiaspina* have so far been described (Taylor 1962, 1992).

Eucalyptus camaldulensis occurs extensively in mainland States where the mean annual rainfall is below 650 mm (Hillis and Brown 1984), and is associated primarily with inland rivers, dry watercourses and floodplains, preferring deep moist subsoils with a heavy clay content. It is an economically important tree as its insect and decay resistant timber is used for house stumps, railway sleepers, fence posts, furniture and firewood (Costermans 1981). It is also of benefit to farmland and rural areas generally, by providing shelter and shade to stock and assisting in reducing water table levels and minimising erosion along streams and rivers as a result of its ability to grow on soils with high salt content. In addition, *E. camaldulensis* provides an important habitat for native wildlife, particularly birds of the drier areas of inland Australia. In recent years the species has become a potential candidate for eucalypt plantation forestry, especially in the northern irrigation areas of Victoria.

At every growth stage, eucalypts in Australian native forests and in rural areas have been variously attacked by a range of insect pests including defoliators, sap-suckers, leaf miners, leaf skeletonizers and wood borers (Morgan and Bungey 1980; Clifton 1988). Among the most devastating of these are the sap-sucking psyllids that feed on a wide variety of eucalypts. Some of these psyllids are restricted to a single eucalypt host species or to a group of closely related species. For example, *Cardiaspina albitextura* (white lace lerp) shows a strong preference for the closely related *E. camaldulensis* and *E. blakelyi* (Blakely's red gum), while *C. retator* (red gum basket lerp) is generally found only on *E. camaldulensis*. Typical eucalypt host species and their psyllid protagonists are summarized in Table 1. While tree mortality seldom results, even after severe attacks (except where these are sustained over a period of years, or where trees are stressed by abiotic factors such as drought and fire damage), growth can be severely affected, leading ultimately to a general decline in tree vigour and to further damage by a range of secondary destructive insects.

This paper examines the biology of psyllids, including their identification, description and life-cycles, and also provides a brief history of psyllid outbreaks in Australia. Emphasis is placed on *E. camaldulensis* as the host for psyllids in a variety of situations including farmland, roadside plantings, eucalypt plantations and native forest. Levels of damage and the impact on growth and tree health are also examined. Suitable options for control of psyllids are discussed to enable landholders and forest plantation managers make informed decisions about ways

of dealing with outbreaks on eucalypts, particularly *E. camaldulensis*.

Table 1. Eucalypt host species and the predominant cardiaspine psyllid species found on each (after CSIRO 1996)

Eucalypt host species	Cardiaspine species hosted
<i>E. blakelyi</i> (Blakely's red gum)	<i>C. albitextura</i> (white lace lerp)
<i>E. camaldulensis</i> (river red gum)	" "
" "	<i>C. retator</i> (red gum basket lerp)
<i>E. fasciculosa</i> (pink gum)	<i>C. densitexta</i> (pink gum lace lerp)
<i>E. grandis</i> (flooded gum)	<i>C. fiscella</i> (brown lace lerp)
<i>E. botryoides</i> (southern mahogany)	" "
<i>E. saligna</i> (Sydney blue gum)	" "
<i>E. robusta</i> (swamp mahogany)	" "
<i>E. grandis</i> (flooded gum)	<i>C. maniformis</i> (finger lerp)
<i>E. melliodora</i> (yellow box)	<i>C. tenuitela</i> (yellow box lace lerp)
<i>E. regnans</i> (mountain ash)	<i>C. bilobata</i> (mountain ash lerp)
<i>E. viminalis</i> (manna gum)	<i>C. sqamula</i> (manna gum lerp)

Life history and description of psyllids

The eggs are generally brown to black in colour, 1 mm long and ovoid in shape, although colour, size, and shape can vary slightly between species. Each female lays between 45 and 700 eggs, either in clusters of approximately 10-150 eggs or in rows on leaf surfaces. Eggs are usually equipped with a stalk, which upon insertion, anchors the eggs to the leaf surface. Following a 10-20 day incubation period, the egg shells split along their length, thereby allowing instar I nymphs to emerge. (Conservation and Environment 1992; CSIRO 1996; Phillips 1996). The newly hatched nymphs (or 'crawlers') move over the leaf surface in search of a stomate for insertion of their stylets and feed on plant sap, usually within 48 hours of hatching. Once settled, they commence construction of a shell (more commonly known as a 'lerp') from starchy material derived from the host plant. It is commonly thought that the lerp structure protects the psyllid insect from predation and desiccation during warm/hot weather. Nymphs usually pass through five instars (or 'moult') before becoming adults. This maturation process to adulthood occurs mostly within the confines of the original lerp. However, occasionally nymphs will move to another feeding site and construct a new lerp. Adult psyllids are generally small (<5 mm length), yellow coloured with black markings and equipped with two pairs of wings. They are strong fliers and jumpers (CSIRO 1996; Phillips 1996).

The number of generations produced per year can vary depending on: (1) the species of psyllid, (2) the prevailing temperatures and (3) the environmental conditions including the availability of leaves suitable for oviposition. However, the usual number is between three and five, with genera such as *Cardiaspina* usually producing three generations per year while

Glycaspis can have up to five and possibly six. Growth and development of nymphal instars occurs throughout most of the year. During warm summer weather the generation turnover is approximately eight weeks from egg to adult compared with six months during cool winter weather (Conservation and Environment 1992; CSIRO 1996). The optimal temperature for growth and development appears to be around 25°C, but feeding and movement can still occur at below 10°C and at higher than 33°C. During warm winter spells, hibernating adults may resume feeding and breeding, thereby allowing additional generations to be produced.

Brief history of psyllid outbreaks in Australia

Psyllids can cause chronic damage to foliage on trees, especially on roadsides and farmlands, and in eucalypt plantations and native forests that are dominated by *E. camaldulensis*. Outbreaks have occurred periodically in Victoria and South Australia, with some as early as 1914 and 1922 when *C. densitexta* (pink lace gum lerp) severely damaged stands of eucalypts in the southeast of South Australia. These attacks were repeated over the 1956-63 and 1967-74 periods, and from 1978 onward into the early 80s, indicating the cyclical nature of attacks (Morgan and Bungey 1980). Attacks on *E. camaldulensis* in South Australia by *C. albitextura* have also been recorded by White (1971) in 1935-36, 1943-45, 1949-50, 1952-53 and 1956-59, while more recently, the psyllid *C. jerramungae* has been implicated in severe damage to stands of eucalypts in the south eastern corner of Western Australia (Farr 1992). In Queensland, outbreaks of *C. fiscella* (brown lace lerp) and *C. maniformis* (finger lerp) have been observed in native eucalypt forests in the south east of the State (Wylie and Peters 1993) whereas, in New South Wales, psyllid species (most probably *C. fiscella*) have been responsible for defoliating stands of *E. camaldulensis* on the Murray River floodplains during 1991-92 (Stone 1993). Moreover, in dry woodland areas of New South Wales (particularly *E. camaldulensis* woodlands), psyllids have sporadically caused high levels of defoliation (Stone 1991). However, this finding contrasts with a report by CSIRO (1996) which claims that in New South Wales *E. camaldulensis* appeared to be relatively free of psyllid damage.

In Victoria, extensive areas of *E. botryoides* (mahogany gum) have occasionally been defoliated by large populations of *C. fiscella*, especially in the Orbost region of East Gippsland between 1951-55 and 1958-63. There has also been chronic damage to *E. camaldulensis* and *E. tereticornis* (forest red gum) by *C. retator* in the Lakes Entrance/Bairnsdale region, resulting in dieback and tree mortality during the 1980s (White 1969; Neumann, F.G. *pers. comm.* 1998). Moreover, outbreaks have been recorded at: Mansfield in north-eastern Victoria during 1943-45 and 1956-63, and Seymour, Euroa and Myrtleford during the mid-1950s, largely as a result of attack by *C. albitextura* (Clark 1962a). Eucalypt plantations (predominantly *E. camaldulensis* plantings) in the northern irrigation area around Shepparton have been damaged by repeated attacks from psyllids including *C. fiscella* and *C. retator*. Since 1990, *E. camaldulensis* plantations on sewage-irrigated sites on the western outskirts of Melbourne have also been partially defoliated by *C. retator*. In the Toorong Plateau/Tanjil Bren area of Central Gippsland, extensive outbreaks of *C. bilobata* (mountain ash psyllid) were first noticed in 1984 within 1939 *E. regnans* (mountain ash) regrowth above 800 m. By 1993, the infestation had reached significant proportions across the

E. regnans resource of Victoria's Central Highlands (Conservation and Natural Resources 1994). Psyllids have also caused chronic problems in windbreaks on farms and in savannah woodlands dominated by *E. camaldulensis* and *E. tereticornis*. Extensive outbreaks in these areas are usually due to *C. albitextura* and *C. retator* (Conservation and Environment 1992).

Mode of attack

Psyllids feed by sucking sap from the tissues of leaves and young plant shoots. While a small attack will result in some leaf discoloration, wilting and distortion in the tree foliage, severe infestations by lerp-type psyllids cause extensive foliage discoloration in tree crowns with purple to brown/rusty red spots, leading ultimately to leaf necroses and defoliation. This loss of foliage in turn reduces tree vigour and slows growth. In situations where psyllid attack has been particularly severe, tree death may ensue, often in conjunction with secondary insect pests infesting the weakened trees.

As psyllids are most active during the summer period, attacked foliage tends to desiccate rapidly due to the warm conditions so that by late summer, leaf fall has accelerated to the point where tree crowns carry little foliage, and in severe situations are totally defoliated. The absence of old foliage, and the presence of dieback among the larger branches, particularly below mid-crown level, are common features in outbreak areas. In ash-type eucalypt forests, dominant and co-dominant trees survive by producing epicormic shoots in response to persistent psyllid attacks, whereas suppressed trees of less than 20 cm DBHOB, whose proportion of living crown has declined to 18%, usually die, thereby aiding the natural thinning process. Seed production may also decline through the early death of capsule-bearing branches (Conservation and Environment 1992, 1994). Studies by Stone and Bacon (1995) have linked the extent of defoliation to moisture stress in trees. They showed that the consumption of *E. camaldulensis* foliage by insects (including sap-sucking psyllids) is greater in non-flooded compared with the flooded areas, and that during drought periods, the leaf abscission rate tends to be higher than in years of 'normal' rainfall.

Causes of psyllid outbreaks

Despite substantial variation in outbreak patterns between different species of psyllid, most conform to the following trends (Morgan 1984):

- Most genera contain species that reach very high densities on occasion, but do not build up to devastating plague levels;
- A species may occur with very high population densities interspaced with low densities in the same generation or year within a region;
- An outbreak of a species may coincide with outbreaks of other species in the same locality, but in such cases usually only one species is predominant;
- An outbreak of a single species may be followed by one of a different species on the same tree in the same area, providing that the host tree recovers from the first outbreak, that is, outbreak 'succession' may occur;
- Outbreaks of most species usually last for approximately three years;

- A decline in an outbreak of a species at one location is often followed by a new outbreak in an adjacent location; even within an original outbreak region, some discrete populations not in synchrony with the main outbreak may develop into new outbreaks as the original one declines; and
- The centres of high population density, and those of subsequent outbreaks, appear to move or flow back and forth across an outbreak region in what is termed an 'outbreak flow'.

These factors indicate that outbreaks of psyllids tend to occur over a widespread area and appear to be cyclical in nature. Hence the research on the causes of psyllid outbreaks has emphasised factors such as weather, plant-growth-cycles and variations in leaf chemistry (Morgan 1984).

Psyllid populations may increase suddenly to outbreak levels when several interacting environmental factors favour their rapid growth, development and generation-turnover. These factors include the following:

- Abundant immature succulent foliage, required by 'young leaf-feeders' such as the free-living blue gum psyllid *Ctenarytaina eucalypti* or ample mature foliage required by 'mature leaf-feeders' such as *C. retator*;
- Host trees growing in single-species forests or plantation monocultures, as mixed species forests or plantations are less susceptible to psyllid outbreaks;
- Leaf nutrient levels sufficiently high to encourage psyllid growth;
- Warmer than average seasonal ambient temperatures boosting generation turnover;
- Enough soil moisture for the host foliage to be fully turgid as this assists the sucking action of the nymphs and adults;
- Absence of flowering in host trees; and,
- Low population levels of indigenous psyllid-specific predators and/or parasitoids, and correspondingly high levels of hyperparasites (Conservation and Environment 1992; Farr 1992).

The available literature suggests that a correlation may exist between outbreaks of psyllids on *E. camaldulensis* and a succession of dry summers combined with very wet winters within the same year. In a study to develop a stress index to measure weather-induced stress of trees associated with psyllid outbreaks, White (1969) established that where tree roots were waterlogged during winter and subject to acute moisture stress in the root zone during the ensuing summer, the trees were particularly susceptible to psyllid outbreaks. Data gathered between 1960 to 1963 around the Mansfield and Orbost districts indicated that the outbreaks occurring in both areas coincided with a positive stress index where summers were very dry relative to the preceding winters. It is important to note that the summer periods in such successions do not necessarily have to correspond to drought conditions. Phillips (1996) also supports the view that in South Australia, psyllid outbreaks may have been related to a similar combination of wet winters and dry summers, as do Ward and Neumann (1982) in Victoria. However, Stone and Bacon (1995) when examining leaf dynamics and insect herbivory in a moisture-stressed

E. camaldulensis forest, found that the consumption of foliage by insects on flooded trees was not significantly different to that on non-flooded trees, although this result related only to a seven-month period (September 1991 to March 1992) during which none of the insect pest species (including *Cardiaspina*) attained outbreak levels.

Clark (1962a) examined psyllid outbreaks (particularly of *C. albitextura*) in the ACT and Victoria during the mid-1950s, and found that lower than average mean daily temperatures coupled with higher than average yearly rainfall levels coincided with an increase in psyllid populations. Psyllid outbreaks in Victoria during the early 1950s at Euroa, Seymour and to a lesser extent Myrtleford, followed a long sequence of below average temperatures. In contrast, outbreaks were not recorded in northern Victoria where seasonal temperatures had remained consistently higher. In all cases psyllid levels eventually fell to low levels primarily due to the desiccation of most of the available foliage over a period of years (thus greatly restricting the food resource and breeding habitat), rather than to changes in average temperature or rainfall. Further studies by Clark (1964) indicated that outbreaks were primarily related to the prevailing weather conditions, particularly ambient temperature, as outbreaks of other *Cardiaspina* species (in addition to those of *C. albitextura*) were recorded in regions of differing soil types, topography and land use.

The mechanism by which declining average temperature induces an increase in psyllid attack has been explained in terms of the unfavourable effect of low temperatures on psyllid-specific chalcidoid wasp parasitoids, such as *Psyllaephagus gemitus* Riek and *P. xenus* Riek (Moore 1961; Clark 1964). Studies on the relationship between the psyllid parasitoids and psyllid population showed that any reduction in parasitoid effectiveness was due to a combination of the following two factors:

- Restrictions placed by the prevailing weather conditions (ie. falling average temperatures) on psyllid/parasitoid synchronism (i.e. their respective populations are no longer acting in phase); and,
- An increase in population levels of hyperparasites capable of decimating the parasitoid populations.

Studies by Moore (1961) have indicated that psyllid-controlling parasitoids may not be capable of attacking psyllid nymphs successfully when the lerp structures are covered with moisture from condensation due to low ambient temperatures. However, this observation relates to *Glycaspis* spp. which have soft hydrophilic lerp coverings, so there is some doubt whether a similar conclusion can be drawn for genus *Cardiaspina* with its hard hydrophobic lerp. While research is not conclusive, it appears that parasitoids, even when present in large numbers, may not always operate as 'density-governing agents'. Some psyllid outbreaks may therefore occur independently of the prevailing parasitoid populations whether they be high or low (Clark 1964).

The role of leaf chemistry in triggering psyllid infestations has been examined by White (1971). He argued that outbreaks occur as a result of an increase in the quality of nutrients available to psyllids, especially soluble nitrogenous compounds in the phloem sap of the foliage of water-logged or drought-stressed trees. While the mechanisms causing this increase in nitrogen

levels are not yet fully understood, it is generally considered that in stressed trees growth is curtailed, and as a consequence, there is an accumulation in the phloem sap of excess nitrogen-rich proteins. These are then broken down into their component amino acids and made available to the psyllids in the sap of still healthy foliage away from chlorotic (yellowing) non-functioning leaves. This hypothesis complements the findings by White (1969) that there is a relationship between moisture stress and amino acid build-up in foliage leading to psyllid outbreaks, and psyllids tend to lay their eggs at the petiole end of the foliage where there is an abundance of soluble nitrogen and other nutrients due to the greater volume of sap.

However, the link between moisture stress in trees and psyllid outbreaks is not always apparent, especially when plantation-grown *E. camaldulensis* is examined. In north central Victoria, especially around the Cobram area, plantation-grown *E. camaldulensis* at age two or older has incurred repeated infestations of *C. retator*. This is despite the plantations being flood-irrigated at regular intervals since establishment (Stackpole *et al.* 1995) and therefore not subjected to moisture stress either through excess or deficit. More recent studies seem to indicate that psyllid outbreaks may be due to a combination of high leaf nutrient levels and low levels of phenolic feeding inhibitors naturally occurring in many eucalypts (Conservation and Environment 1992).

A comprehensive review by Morgan (1984) of all the known variables causing an increase in psyllid populations has placed less emphasis on single factors, such as high soluble nitrogen levels in the foliage as argued by White (1971), and more on when certain critical instars synchronize with factors such as: (1) an abundance of leaves of appropriate age on tree hosts, (2) low levels of phenolic feeding inhibitors within the foliage, (3) adequate nutrient supplies, (4) foliage in a turgid state, and (5) the ineffectiveness of natural controls. The effects of phenolic feeding inhibitors have come under more study. When adult psyllid populations were placed on foliage with known phenolic levels, there was a positive correlation between the concentration of phenolics and psyllid mortality (Table 2). Tree flowering also seems to play a role in making foliage less attractive to psyllids by redirecting nutrients and thereby altering leaf quality. However, more research is required to establish the mechanism involved in this physiological change.

Table 2. The influence of total phenolics in the leaves of *Eucalyptus camaldulensis* on population losses of *Cardiaspina albitextura* (after Morgan 1984)

Concentration of total phenolics (% dry weight of leaves)	Population loss (%)
7	18
8	31
9	46
10	62
11	76
12	77
13	83
14	79

The view that drought stress alone is not solely responsible for psyllid outbreaks during drought periods is supported by the observation that exceptionally dry summers and winters in recent years in Victoria and southern New South Wales have not so far resulted in widespread psyllid outbreaks in forests or in farmland. However, it is uncertain whether this situation of zero outbreaks will continue once sufficient rainfall is received and the ambient temperatures fall. While widespread psyllid damage has not been recorded, localised psyllid defoliation has nevertheless been observed in some places, particularly in small stands of *E. camaldulensis* on farms and roadside plantings where land clearance may have adversely affected natural control agents and caused water tables to rise (Wouters 1993).

Control of psyllids on *E. camaldulensis*

General considerations

Psyllid outbreaks, whether on single farm trees, on roadside plantings, in natural forest stands or increasingly, in eucalypt plantations, require constant monitoring to ensure psyllid populations do not reach unacceptable levels and cause excessive loss of foliage, a decline in tree vigour and growth and, in extreme circumstances, tree mortality. The main options currently available for psyllid control fall under the headings:

- direct control;
- biological control;
- cultural control;
- genetic control.

Direct control involves the use of pesticides or physical control measures, while biological control concerns the actions of indigenous predators such as birds, various insects, spiders, mites and fungi in limiting pest populations. Cultural control relates to the tending and caring of trees to encourage healthy growth, thus enabling them to be better able to withstand and recover from damaging attacks. Genetic control involves the selection of genetically resistant genotypes for use in plantings as well as the genetic manipulation of biological control agents to increase their efficacy against the target pest.

An important aspect in psyllid management is not only to appreciate when to implement control measures, but more importantly, when not to apply them. Any decision to proceed with any of the above controls depends on a number of factors including: (1) the severity of attack, (2) the prevailing climatic conditions (e.g. drought) which may contribute to excessive loss of tree vigour/mortality, and (3) the purpose for which the trees are being grown. In the latter case, compared with, say, trees in a roadside stand, a commercial eucalypt plantation may require a more concerted control effort in order to maximise returns over short rotations.

Recent studies into the effects of defoliation on height and diameter growth of plantation-grown *E. globulus* and *E. grandis* (flooded gum) have indicated that a single defoliation in the spring, whether it be of the whole crown or of the upper and lower 50% of the green crown, has minimal impact on tree growth. Alternatively, a single defoliation in autumn of the total crown or of the upper 50% of crown impacts adversely on tree growth (Neumann *et al.* 1997). As most psyllids tend to concentrate their initial attack on the older, less vigorous lower

canopy foliage, control may not be necessary providing that psyllid levels do not increase and start attacking the upper canopy. Further research is required in order to establish whether the results obtained for *E. globulus* and *E. grandis* are also applicable to *E. camaldulensis*.

Direct control

The control of psyllid populations with chemical insecticides is a viable option only in plantations or on individual or small stands of trees where the spraying program is confined to a restricted area. Spraying of outbreaks in extensive forest areas is not an option except possibly in specific circumstances threatening large-scale tree mortality. This is because the spray can affect non-target insect populations including psyllid predator/parasitoid species, operational costs can be high and there are environmental concerns relating to pollution and risks to human health.

Chemical control can be conducted in two ways: the first involves the direct application of a contact or systemic insecticide to affected foliage, and the second, stem injection of systemic insecticides into the trunk of host trees. In direct applications to the foliage, a single application of an appropriately registered contact insecticide is usually effective for controlling two to three generations of psyllids. Repeat applications may be necessary for longer-term protection, especially where new growth is prolific soon after spraying and the new foliage is attacked from outside the sprayed area (Conservation and Environment 1992). Trials conducted in 1972 at Tintinara, South Australia, on the effects of chemicals on *C. densitexta* found that seven days after psyllid-affected foliage was sprayed, four treatments viz. 0.2% and 0.4% malathion, and 0.2% and 0.4% imidan (common name 'phosmet') (Tomlin 1995), resulted in 100% mortality for up to two generations of the insect (Morgan 1984). Any use of these chemicals in control programs within Australia, however, are subject to the chemical being appropriately registered, and their meeting all legal requirements for use in that particular state.

Stem injection with systemics is impractical in large plantations or native forests due to the large numbers of trees involved and the associated labour costs. However, it may be appropriate where individual or small stands of trees in parks, gardens, roadside plantings or on farms are too tall for spraying from the ground, and where environmental constraints do not allow the use of toxic chemicals. The stem injection technique to control psyllids in eucalypts was first developed in Western Australia and involved the injection of the insecticide dimethoate with a syringe into the tree stem 1.3 m above the ground through approximately 12.5 mm diameter holes drilled to the full depth of the sapwood at an angle of 30-45° (Wallace 1966). It is important in such operations to ensure that the timing of stem injection coincides with the egg hatching period. Because stem injection requires an upward flow of the sap to translocate the insecticide into the foliage, treatments should not be done during drought periods when sap flow is minimal. A second injection two months later may be required especially where trees have large crowns and the insecticide is diluted. However, Morgan (1984) found in trials that at least one year of effectiveness and possibly more could be achieved when systemic chemicals were injected into the trunks of even large trees. As previously observed, however, use of these chemicals within Australia is subject to the chemical being appropriately registered and meeting all legal requirements for use in the

particular State. Other available data indicate that microbial insecticides, such as *Bacillus thuringiensis* (Bt), are ineffective against psyllid infestations (CSIRO 1996), presumably because they act only after ingestion by the target insect.

Biological control

Indigenous predators such as birds, spiders, mites, certain insects (e.g. wasp parasitoids) and insectivorous fungi (e.g. *Beauveria spp.*), are some of the natural agents that assist in biological control of psyllids (Conservation and Environment 1992). Wasp parasitoids of the genus *Psyllaephagus* have been shown to control low populations of psyllids, with their efficacy dependent on prevailing weather conditions. However, at high psyllid densities during outbreaks, parasitoids have not had much impact on psyllid numbers (CSIRO 1996). Other insects such as the nymphs and adults of praying mantids and some hemipteran bugs, the larvae and adults of lacewings and ladybird beetles, the larvae of syrphid flies and the adults of some ant species also contribute to natural control. However, as with psyllid-specific parasitoids, these predators are known to contribute only marginally to psyllid control (Conservation and Environment 1992; Phillips 1996). Birds such as willie wagtails, honeyeaters and Pardalotes also assist in controlling psyllid levels. However, instances have occurred in Victoria and New South Wales where predating bell miners (*Manorina melanophrys*) have reduced the overall efficacy of the insectivorous bird complex through their aggressive territoriality, resulting in the expulsion of more effective predating bird species from psyllid infested forest areas (Ward and Neumann 1982; Stone 1996).

Biological control techniques such as the mass-breeding of parasitoids for localised release to supplement naturally occurring populations, and the importation from overseas of suitably screened parasitoids for release, have been suggested by Morgan (1984). However, these methods would run into many potential problems including:

- The difficulty of providing the right environment for mass rearing, and timing their release;
- Inadequate knowledge of the number of parasitoids required to effectively 'swamp' a breeding psyllid population;
- The costs involved in such long-term programs;
- The delays through quarantine restrictions in screening suitable overseas parasitoid candidates;
- The potential difficulties of synchronizing the life-cycles of introduced parasitoids to those of native psyllids; and
- The fact that indigenous psyllids have long been exposed to a wide range of natural enemies, and have therefore evolved effective survival mechanisms.

In light of the available information, it seems likely that biological control, at least in the foreseeable future, will assist only marginally in limiting psyllid populations, and that given favourable environmental conditions, psyllid populations will continue to increase independently of prevailing predator levels.

Cultural control

The use of cultural control (i.e. the tending and caring of trees or the deliberate diversification of the flora through planting to

minimize damaging pest outbreaks) is generally restricted to commercial plantations and isolated plantings in parks, gardens and roadsides. Psyllid outbreaks in plantations of *E. camaldulensis* can be minimised by interplanting other non-susceptible eucalypts such as *E. globulus* and shrubs as it encourages the influx of a wide range of predator species as well as increasing the spacing between susceptible trees (Conservation and Environment 1992). The establishment of mosaics of small monocultures, each approximately 0.25 ha in area, may also be effective provided that blocks of resistant trees are planted adjacent to blocks of more susceptible trees (Conservation and Environment 1992).

Pruning and thinning may also assist in reducing psyllid levels when applied correctly. In *E. camaldulensis*, high levels of *C. albitextura* or *C. retator* are often found on the lower branches of trees at the beginning of outbreaks. If these lower branches are removed after oviposition, damaging outbreaks could be averted. In more severe cases, where large numbers of psyllids have established on some individual trees, indicating their susceptibility, such trees should be felled and burnt. Burning and thinning are best done when psyllid populations are still confined to a few highly susceptible trees during periods favourable to psyllid outbreaks (Conservation and Environment 1992; Morgan 1984). Old open-grown psyllid-infested *E. camaldulensis* trees in pastures and paddocks, are best treated by pruning off about two-thirds of all major branches to encourage the growth of young, more resistant foliage, thereby rejuvenating the tree crowns (Conservation and Environment 1992). Furthermore, chemical defoliants may be applied during spring to temporarily defoliate individual trees, thereby controlling psyllid levels on them without significant loss of growth as trees should recover rapidly in late spring. The use of chemicals, however, is risky unless done with care as the effects of defoliants, combined with climatic stress, may result in dieback or tree mortality. Research is required to 'fine-tune' the correct use of defoliants for psyllid control in plantations.

Genetic control

The genetic control technique with most chance of success in Australia involves the selection of eucalypt material displaying inherent resistance to attack in psyllid-susceptible plantations. The genetic manipulation of biological control agents to increase their efficacy against psyllids is not currently considered a viable option as psyllids are native pests already genetically attuned to the full complement of local predator/parasitoid species and, the known biological control agents tend to be ineffective as 'density governing agents' even when psyllid population levels are low (Clark 1964).

Some eucalypt species hybridise, creating genotypes with a marked resistance to insect attack, for example the hybrid cross between *E. torquata* (coral gum) and *E. woodwardi* (Woodward's blackbutt) is a tree displaying pronounced resistance to *Uraba lugens* (gum leaf skeletoniser) (Morgan 1984). *Eucalyptus camaldulensis* also hybridises well with a range of eucalypt species, although it is not known whether any of these hybrids are manifestly resistant to psyllids or other insect pests. Furthermore, insect resistance in a hybrid may be obtained at the expense of such characteristics as good form, above average height and diameter growth and desirable wood properties.

Studies have been conducted to examine inter- and intra-provenance variation in *E. camaldulensis* foliage to a range of insect pests, including *C. albitextura* and *C. retator*. The use of insect-resistant material is advantageous as it provides an alternative means of controlling pests such as psyllids without having to resort to the use of environmentally undesirable and costly pesticide applications. Clark (1962b), White (1971) and Floyd *et al.* (1994) have all demonstrated the existence in *E. camaldulensis* provenances of marked variation in insect pest resistance, both between and within distinct provenances, although this variation was never quantified nor the mechanism determined by the first two authors. Trials conducted by Floyd *et al.* (1994) at Seymour, Tatura and Tumut (NSW) in the early 1990s established that provenances of *E. camaldulensis* from Mannawarra and Silvertown in the Lake Frome catchment and the Lake Bolac provenance were markedly more resistant to insect pests, including *C. retator*, than the provenances at the trial sites near Seymour and Shepparton (Tatura). While the mechanisms of resistance are not completely understood, it is thought that either the waxes on the leaf surfaces (as in the Mannawarra and Silvertown provenances) or the thick hard leaves (in the Lake Bolac provenance) are possible factors responsible for the observed resistance. The reasons why the provenances from the trial areas were the most susceptible are not clearly understood, but it was suggested by Floyd *et al.* (1994) that this may have been due to either the local insects being more adapted to the local provenances or, a lack of ecological equilibrium between insects and hosts in the highly disturbed agricultural landscape.

When intra-provenance variation to insect attack was examined, Floyd *et al.* (1994) found that *E. camaldulensis* from the Lake Albacutya provenance included phenotypes of both high and low insect susceptibility. This raised the possibility of using the 'resistant' phenotypes in resistance breeding programs, although not all trees raised from resistant parent trees would necessarily be resistant as genetic material from insect-susceptible trees could be 'masking' the genes conferring insect resistance.

Integrated Pest Management (IPM) of psyllids

When deciding on control measures against psyllids, the most attractive approach is to use a combination of some or all of the four methods discussed above (a multipronged approach) where possible, rather than relying on a single method of control. For example, the repeated use of chemicals against psyllids could conceivably lead to the development of resistance within target insects to the particular chemical used, thereby rendering the chemical unsuitable; and the application of only cultural controls, such as lower branch removal on susceptible trees, may still not prevent damaging outbreaks if there is a steady influx of pest insects from outside the plantation.

A combination of: (1) chemical control timed to coincide with the oviposition period and with minimum insecticidal concentrations, (2) cultural controls such as the timely removal of lower susceptible branches, (3) the planting of small blocks of resistant species of eucalypts interspersed with *E. camaldulensis*, and (4) the phasing into plantations of resistant (or less susceptible) provenances of *E. camaldulensis* will assist in either preventing or lessening the effects of damaging psyllid attack. The methods selected will depend greatly on factors such as the type of stand to be protected (e.g. *E. camaldulensis* in commercial plantations, in windbreaks or in small shade-providing woodlots on farms), and the constraints imposed on their use. For example, chemical spray applications

are not to be recommended in situations where stands of trees are adjacent to water supplies for fear of contamination and risks to the health of humans and farm animals.

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