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Integrated Pest Management of Eucalypt Psyllids (Insecta, Hemiptera, Psylloidea)

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1. Introduction

Eucalypts, which are native to Australia, grow rapidly and have multiple uses. Because of these properties, they are planted on all continents except for Antarctica. In Brazil, many eucalypt species find suitable weather and environmental conditions to develop and today they are commercially grown on a large scale. In 2010, plantations covered a surface of over 4.75 million hectares (ABRAF, 2011). In Australia, eucalypts host an abundant fauna of phytophagous insects, among which the jumping plant-lice (Hemiptera: Psylloidea) are particularly species rich.

Psyllids are tiny sap-sucking insects resembling minute cicadas and they generally develop on woody dicotyledons (Hodkinson, 1974; Burckhardt, 1994; Hollis, 2004). Most species have very restricted host plant ranges. Larvae can be free-living or develop in open or closed galls, whereas others build waxy coverings, called lerps, under which they develop (Hodkinson, 1984, 2009; Hollis, 2004; Burckhardt, 2005). The subfamily Spondyliaspinae (Aphalaridae *sensu* Burckhardt & Ouvrard, 2011) is almost exclusively restricted to Australia and to host plants of the Myrtaceae, in particular *Eucalyptus* species (Burckhardt, 1991; Hollis, 2004). Unsurprisingly, several Australian spondyliaspine species have been introduced into other continents where they have become pests (Burckhardt, 1994; Burckhardt et al., 1999; Hollis, 2004).

In Brazil, the first spondyliaspine found was *Ctenarytaina spatulata*, when it was observed in 1994 in a *Eucalyptus grandis* plantation in Paraná State (Iede et al., 1997). Another three species infesting eucalypts were introduced into Brazil within a decade: *Blastopsylla occidentalis* in 1997, *Ctenarytaina eucalypti* in 1998, and *Glycypis brimblecombei* in 2003 (Maschio et al., 1997; Burckhardt et al., 1999; Wilcken et al., 2003).

In this chapter, we present information on eucalypt psyllids that are pests outside Australia with particular emphasis on the situation in Brazil. This information constitutes the necessary base to control these pests. Some of the control options are also discussed.

2. Jumping plant-lice

Psyllids, or jumping plant-lice, are small phloem-feeding insects, measuring 1–10 mm body length. Together with the white flies, aphids and scale insects they constitute the suborder Sternorrhyncha within the Hemiptera. Currently, 3850 species have been described worldwide (Li, 2011), which is probably less than half of the existing number of species. Bekker-Migdisova (1973) suggested that psyllids are a very old group already represented in the Permian by the extinct family Protopsyllidiidae. According to Klimaszewski (1964), the major diversification of Psylloidea occurred between the Middle Jurassic and the Middle Cretaceous, which would coincide with the major diversification of angiosperms. More recent studies, however, imply that origin and diversification of Psylloidea may be much younger. Grimaldi (2003) showed that Protopsyllidiidae may constitute the sister-group of all Sternorrhyncha. Host plant and biogeographic evidence presented by White and Hodkinson (1985) further suggests that the modern psyllids evolved in Gondwana from an ancestor associated with the plant order Sapindales. The Mesozoic Liadopsyllidae form a potential sister-group of modern Psylloidea and the latter are represented in the fossil record only from the Eocene and later (Ouvrard et al., 2010).

As with other hemipterans, psyllids have piercing-sucking mouth-parts. When feeding, the mandibular and maxillary stylets are inserted into the host tissue, saliva is injected and then the liquid food is absorbed. Before feeding, the insects probe more or less extensively. The probing also involves injection of saliva, which is particularly relevant in species which transmit bacterial or viral pathogens. As with other Sternorrhyncha and many Fulgoromorpha, psyllids are specialised phloem-feeders and display several adaptations for coping with this unbalanced, nitrogen-poor diet. The anterior and posterior portions of the mid-gut form a loop which permits water to pass directly from the fore- to the hind-gut. The excess water with dissolved sugars is excreted as honeydew. The often copious production of waxy secretions is a result of the hydrocarbon-rich phloem sap. Psyllids possess bacterial endosymbionts which are situated in the mycetome, a specialised organ in the abdomen. Thao et al. (2000, 2001) showed that psyllids and their primary prokaryotic endosymbionts co-speciated.

Unlike in the related aphids, the life cycle of psyllids usually consists of the egg stage, five larval instars and sexually reproducing adults. The ratio of males/females is near to 1:1 (Hodkinson, 2009). Most psyllid species complete their larval development on one or a few closely related plant species. Adult psyllids are always winged and are easily dispersed by wind. They also have large metacoxae, fused to the metathorax, containing strong muscles enabling them to jump, hence their names 'psylla' from Greek 'flea', or 'jumping plant-louse'. Most psyllids are well camouflaged on the substrate they live and remain generally unnoticed. As a result of these properties, they are predisposed to be accidentally transported by humans together with their host plants or accidentally dispersed by wind over large distances. Psyllids are attracted by yellow colours, a fact which is exploited in monitoring pests with yellow water or sticky traps.

Free living psyllid larvae, depending on the species, sit in the leaf or flower buds or along the veins of young leaves. Some species are covered in copious waxy secretions, which provide defence against soiling with honeydew, desiccation, and also protection against

predators and parasitoids. An extreme form of this is found in some species of Spondyliaspidae, Pachyphylloinae or Macrocorsinae which construct lerps, i.e. shields consisting of wax and sugar which often display a very characteristic shape, structure and chemical composition (Moore, 1961; Hollis, 2004). Many psyllids develop in galls (Hodkinson, 1984; Burckhardt, 2005), which are generally induced by the first instar larva. The insertion of the stylets triggers increased cell growth around the larva, which may cover it completely. In *Apsylla cistellata*, the feeding of the first instar larva on leaves induces cell growth in the leaf buds farther away. Later, the second instar migrates into the already formed gall (Raman et al., 2009). Galls can be open, called pit galls, or closed and resemble small nuts, discs or globes (Hodkinson, 1984; Yang & Mitter, 1994). Yang et al. (2000) described a case of inquilinism. Newly hatched first instar larvae of *Pachyphylloa cohabitans*, which are unable to induce galls, feed next to larvae of several other gall-inducing *Pachyphylloa* species and become incorporated into the growing gall.

Depending on the climatic conditions, psyllid species of temperate regions tend to be univoltine or bivoltine, while those of the tropics are often polyvoltine, with several overlapping generations per year (Burckhardt, 1994; Hollis, 2004; Santana et al., 2010). Hodkinson (2009) analysed the life history characteristics of 342 psyllid species from all over the world and concluded that environmental temperatures and water availability acting on the psyllids, directly or via the host plant, are the major determinants of psyllid life cycles. The phenology of psyllids is, therefore, well synchronised with that of their hosts. Psyllid populations are generally controlled by a whole range of predators and parasitoids (Hodkinson, 1974; Hollis, 2004). Birds and small mammals are known to occasionally eat psyllids. In agricultural systems, anthocorids, syrphids, coccinellids and chrysopids are sometimes capable of controlling psyllid populations, but parasitoids such as encyrtids and eulophids are usually more efficient. Psyllids are also affected by entomopathogenic fungi, with which they may be controlled (Dal Pogetto et al., 2011).

Psyllid host plants are mostly perennial dicotyledonous angiosperms. There are only a few psyllids associated with monocots, such as the holarctic genus *Livia*. Even less species develop on gymnosperms, most notably some triozids in New Zealand and two species of *Ehrendorferiana* from southern Chile (Hodkinson, 2009). Restricted host ranges characterise not only psyllid species but, to a certain extent, also higher taxonomic ranks. Related psyllid species tend to breed on related plant species. Members of the tropical family Homotomidae are all associated with *Ficus* species and other Moraceae (Hollis & Broofield, 1989) and those of its putative sister-group, the Carsidaridae, are associated with members of the Malvales (Hollis, 1987). This pattern suggests that there may be co-speciation between angiosperms and psyllids. Detailed phylogenetic studies, however, show that the observed species richness in psyllids is better explained by geographic vicariance than by co-speciation with the host-plants (Burckhardt & Basset, 2000; Percy, 2003; Burckhardt & Ouvrard, 2007).

Within modern Psylloidea, three probably monophyletic lineages exist (Burckhardt & Ouvrard, 2011), namely: 1. Phacopteronidae; 2. Aphalaridae + (Carsidaridae + Homotomidae); and 3. Liviidae + (Calophyidae + (Psyllidae + Triozidae)). Host associations with the plant family Myrtaceae occur in the following taxa: Aphalaridae (Spondyliaspidae), Liviidae (Diaphorininae) and Triozidae. This suggests that psyllids

colonised Myrtaceae at least three times independently. The Spondyliaspidae comprises 24 genera (Burckhardt, 1991; Hollis, 2004), with species which breed almost exclusively on Myrtaceae and which are restricted to the Australian region. The monotypic Oriental genus *Eurhinocola* is an exception, as it is not represented in the Australian fauna. The genus *Boreioglycaspis* has species in Australia and southeast Asia and is associated with Myrtaceae and the related Lythraceae. *Ctenarytaina* has an even wider distribution, including species native to New Zealand, southeast Asia, China, the Indian subcontinent, and possibly even tropical Africa. It is also wider in its host associations and has some hosts outside the Myrtales.

3. Eucalyptus

Members of the eucalypt group (Myrtaceae) of trees and mallees (shrub forms) represent an old lineage that can be related back to the Late Cretaceous, indicating their Gondwanan origin. There are well in excess of 700 species, with most being confined to Australia, although 15 species naturally occur outside of Australia in southeast Asia, as distant as Sulawesi and the Philippines, and related genera occur in New Caledonia. Australian representatives of the group were originally regarded as two genera, *Eucalyptus* and *Angophora* (Burbidge, 1960). More recently, seven genera within the group have been recognised (Ladiges, 1997), with the main genus being split into *Eucalyptus* L'Hér. *sensu stricto* (+600 species) and the bloodwoods, *Corymbia* Hill & Johnson (+100 species), which are of equal taxonomic rank to *Angophora*. Within the genus *Eucalyptus*, a number of subgenera are recognised (Brooker 2000), namely *Acerosae*, *Alveolata*, *Cruciformes*, *Cuboidea*, *Eucalyptus*, *Eudesmia*, *Idiogenes*, *Minutifructus*, *Primitiva*, and *Symphomyrtus*. The other genera within the eucalypt group which, with one exception, are monotypic, are *Arillastrum* (New Caledonia), *Allosyncarpia* (northern Australia), *Eucalyptopsis* (New Guinea, Moluccan Archipelago, Woodlark Island) and *Stockwellia* (northern Australia).

Considering the antiquity of the 'eucalypts', it is not surprising that invertebrates have co-evolved to feed on or utilize other resources from these trees. Working in the canopy alone, Majer et al. (2000) sampled 641 and 726 invertebrate species from *Eucalyptus moluccana* and *E. crebra* in NSW, eastern Australia and 448 and 444 from *E. marginata* and *Corymbia calophylla* in WA, western Australia. In all instances, the percentage of herbivores in the count ranged from 20.5–25%. The richness of herbivores on 'eucalypts' is accompanied by high degrees of specificity of certain groups to 'eucalypt' species or subgenera. This has been observed in gall-forming eriococcid scale insects (Cook, 2001; Cook & Gullen, 2004), where particular species have been found to be specific to certain species of *Eucalyptus* or *Corymbia*. Another example is the Australian psyllids (Aphalaridae: Spondyliaspidae), which are renowned for their association with 'eucalypts', with 67% of species utilising 'eucalypts' as host plants (Majer et al., 1997). Working on the 'eucalypt'-feeding genus *Glycaspis*, Moore (1961, 1970) was able to divide the genus into subgenera on the basis of morphology and host plant association. This is but one example of the high degree of host-specificity of Australian psyllids on 'eucalypts'.

Hosts	<i>C. spatulata</i>	<i>C. eucalypti</i>	<i>B. occidentalis</i>	<i>G. brimblecombei</i>
<i>E. benthamii</i>		x		
<i>E. bicostata</i>		x		
<i>E. blakelyi</i>			x	
<i>E. brassiana</i>			x	
<i>E. bridgesiana</i>				x
<i>E. camaldulensis</i>		x		x
<i>E. camphora</i>				x
<i>E. dealbata</i>				x
<i>E. diversicolor</i>				x
<i>E. dunnii</i>		x		
<i>E. forrestiana</i>			x	
<i>E. globulus</i>		x	x	x
<i>E. gomphocephala</i>			x	
<i>E. grandis</i>	x		x	
<i>E. maidenii</i>		x		
<i>E. mannifera</i>				x
<i>E. mannifera maculosa</i>				x
<i>E. microneura</i>			x	
<i>E. microtheca</i>			x	
<i>E. nicholii</i>			x	
<i>E. nicholsii</i>			x	
<i>E. nitens</i>		x		x
<i>E. oleosa</i>			x	
<i>E. pellita</i>	x			
<i>E. pulverulenta</i>		x		
<i>E. robusta</i>	x			
<i>E. rudis</i>			x	
<i>E. saligna</i>			x	
<i>E. sideroxylon</i>				x
<i>E. spathulata</i>			x	
<i>E. tereticornis</i>			x	x
<i>E. urophylla</i>	x		x	

Table 1. Lists the four Australian psyllids that have become established in Brazilian eucalypt plantations, showing their main hosts in Brazil (in bold) and also the other species that they can exploit (sources: Burckhardt et al., 1999; Brennan et al., 2001; Hollis, 2004; Meza & Baldini, 2001). All host species are members of the *Symphomyrtus* subgenus.

4. Psyllid pests and eucalypts

Due to the close association with their hosts, some psyllids are of economic relevance. While most of these are minor pests (Burckhardt, 1994), a few species are responsible for huge economic losses, such as the species transmitting bacterial phytopathogens (e.g. *Diaphorina citri*, some *Cacopsylla* spp., *Bactericera cockerelli*) (Hodkinson, 2009) or the eucalypt psyllids (Santana & Burckhardt, 2007).

Over 350 species of Psylloidea are reported from Australia (Hollis, 2004), of which 79% are associated with Myrtaceae and 71% with eucalypts. In Australia most populations of eucalypt psyllids are in balance (Collet, 2001a). However, when introduced into other continents, their populations may increase and become a serious problem (Paine & Millar, 2002). This has been the case with *Ctenarytaina eucalypti* (Dahlsten et al., 1998a; Pinzón et al., 2002) and *Glycaspis brimblecombei* (Bouvet et al., 2005). Currently, seven Australian species are known from other continents (*Blastopsylla occidentalis*, *Cardiaspina fiscella*, *Cryptoneossa triangula*, *Ctenarytaina eucalypti*, *C. spatulata*, *Eucalyptolyma maideni*, and *Glycaspis brimblecombei*). An eighth species probably also originates from Australia but has not yet been found there. It is *Ctenarytaina peregrina*, which was described from Eire (Hodkinson, 2007) and has later been found in Germany (K. Schrameyer, pers. comm.).

4.1 *Ctenarytaina spatulata* Taylor, 1997 (rose gum psyllid)

Ctenarytaina spatulata originates from southeast Australia and has been introduced into New Zealand, the USA (California), Uruguay, Brazil, Portugal and Spain (Burckhardt et al., 1999; Santana et al., 1999; Hollis, 2004; Valente et al., 2004). It was observed for the first time in Brazil in Arapoti – Paraná State in 1994, in an *E. grandis* plantation (Burckhardt et al., 1999). It is now commonly found in the states of São Paulo, Paraná, Santa Catarina and Rio Grande do Sul.

The adults of *C. spatulata* (Fig. 1A) are yellowish or orange with dark spots or dark brown stripes. The forewings are transparent and yellowish with slightly darker veins. They remain most of the time on the leaves and new apical shoots, where they feed and reproduce. The females lay their eggs (Fig. 1B) on the newly growing leaf axils (Santana & Zanol, 2006).

All five larval instars have a dorso-ventrally flattened body. They live in colonies and feed on young plants or shoots. They secrete large amounts of honeydew which is secreted as small wax-covered globules together with a large amount of flocculent waxy secretions along the sides of the abdomen, which spread out all over the colony (Santana & Zanol, 2005). Honeydew and waxy secretions harm the development of the young plants, particularly in the first two years of planting (Collet, 2001a). In the first larval instar, the body is entirely yellow, except for the small red eyes. In the final instar larva, the length of the body is 1.40–1.43 mm. The body is brown to yellowish with brown patches (Fig. 1C). The caudal plate bears five lanceolate setae on each side of the anus. The wing buds are well-developed; the forewing buds lack a humeral lobe, and their fore margin lies posterior to the posterior eye margin (Taylor, 1997; Santana & Zanol, 2005).

C. spatulata is associated with several *Eucalyptus* spp., in particular with *E. grandis*, *E. saligna*, *E. robusta*, *E. pellita*, *E. resinifera* and *E. urophylla*, but it has also been observed in lower

numbers on *E. deanei*, *E. saligna*, *E. tereticornis*, *E. microcorys*, *E. viminalis*, *E. camaldulensis*, *E. alba* and *E. nitens* (Santana, 2003). Among the species of *Corymbia*, only eggs of *C. spatulata* have been observed on adult leaves of *C. citriodora*. Neither eggs nor larvae of *C. spatulata* have been observed on native Myrtaceae in Brazil (Santana, 2003). Valente et al. (2004) found *C. spatulata* mostly on *E. globulus*, the main eucalypt species planted on the Iberian Peninsula. This eucalypt is also a major host of *C. spatulata* in California (Brennan et al., 2001). These authors also observed large populations of the psyllid on *E. nitens*, *E. dalrympleana* and *E. maidenii*. Other host species mentioned in the literature are *E. leucoxydon*, *E. mannifera maculosa*, *E. pauciflora*, *E. longifolia*, *E. rodwayi*, *E. ovata*, *E. nitida* (Taylor, 1997), *E. amplifolia*, *E. dunnii*, *E. robusta*, *E. rostrata* and *E. tereticornis* (Burckhardt et al., 1999).

In Brazil, this species has many generations per year, leading to a higher number of individuals during the cold and dry months (Santana & Burckhardt, 2007).

The damage of this pest was observed on *E. grandis* in Paraná state and hybrids of *E. grandis* x *E. urophylla* in São Paulo, with symptoms including sooty mould on the leaves and tips, dieback, loss of apical dominance, super sprouting and decrease of growth (Santana et al., 2005). *C. spatulata* completes its life cycle from egg to adult at temperatures around 20 °C in approximately 45 days (Santana & Zanol, 2006). In São Paulo and Paraná all life stages of the species can be observed during the entire year (Santana, 2003). The first damage by *C. spatulata* to *E. grandis* is caused by oviposition (Santana et al., 2005). A small black spot appears where the egg is inserted, which may increase and lead to withering of the terminal buds. The larvae secrete large amounts of honeydew, which accumulates on leaves and buds, allowing the growth of sooty mould and phytopathogenic fungi. The successive piercing of the substrate and the extraction of plant sap causes deformations and curling of the leaf, thus reducing the leaf surface. High populations weaken the plant further by the extraction of plant sap, causing the death of the terminal buds, the loss of apical dominance and super sprouting of the lateral buds (similar to formation of witches' brooms by excessive growth of lateral buds) (Cadahia, 1980; Zondag, 1982; Meza & Baldini, 2001; Santana et al., 2005).

In addition, the sucking of *C. spatulata* can reduce the increment of stem diameter and of the internodes, resulting in more branches on the stem and rendering the wood of the stem more fragile (Santana et al., 2005). The damage caused by *C. spatulata* in Brazil has been estimated in a green-house (Santana et al., 1999). By studying the nutritional stress, the authors observed that there is an interaction between the insects and Mg deficiency. Both factors together may stop growth and production of biomass, in addition to affecting root development. The research done in the greenhouse and the field shows that *C. spatulata* appeared in all samples, with 100% occurrence of larvae and eggs. Its presence was observed during all months of the year, in every stage, which is typical for a polyvoltine life cycle. It also has a population peak in the colder months with low rainfall (Santana et al., 2005).

Water stress is one of the environmental factors that may improve the development of the psyllid population (White, 1969) due to higher nitrogen concentration in the plants. Santana et al. (2003a) simulated water stress in *E. grandis* plants, with and without the presence of *C. spatulata*, and noticed that the insects may cause a 20% loss of height growth in *E. grandis*. The combination of water stress and presence of the insects may cause considerable damage.

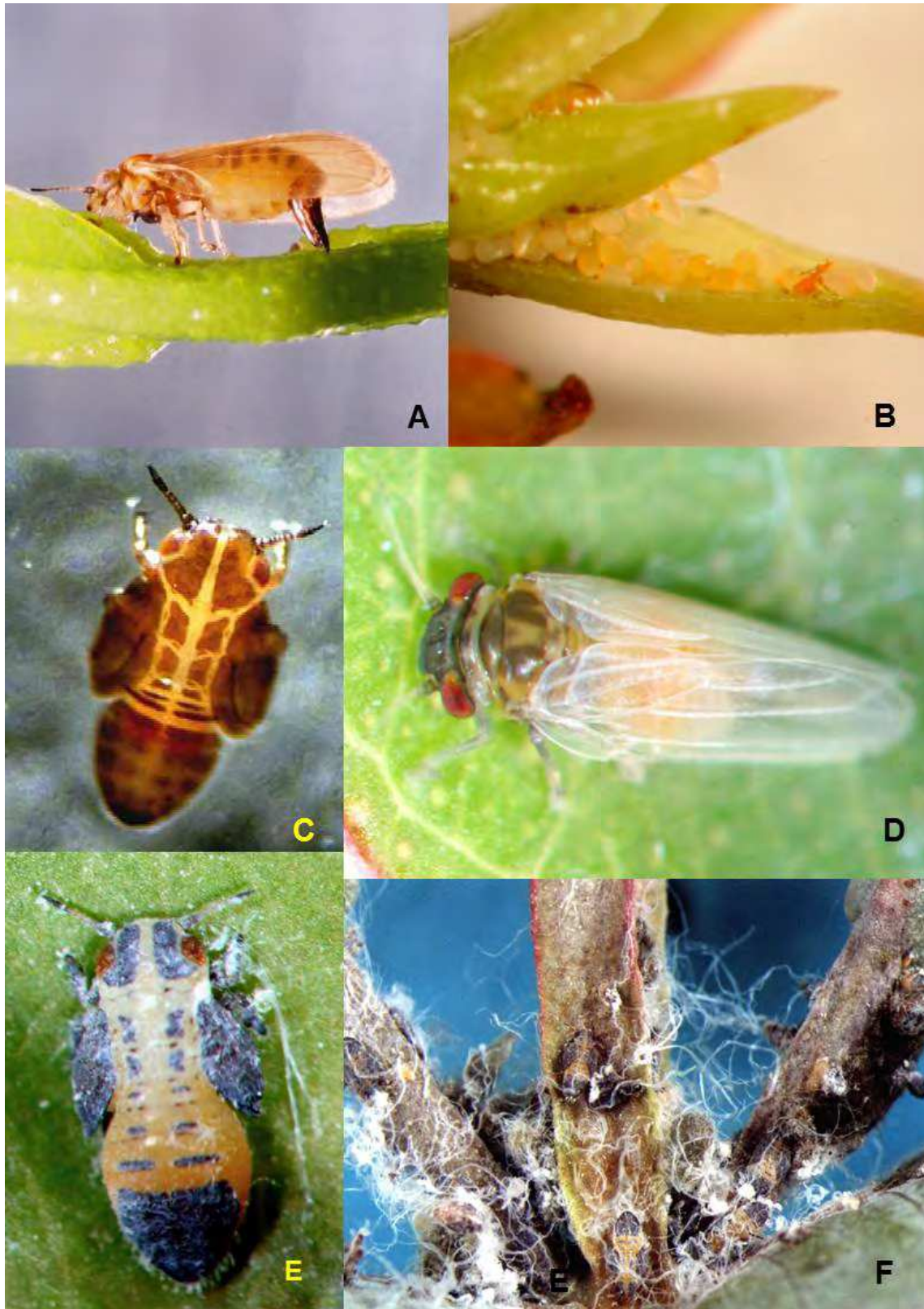


Fig. 1. *Ctenarytaina spatulata* (A - adult, B - eggs, C - larva); *C. eucalypti* (D - adult, E - larva, F - colony of larvae).

4.2 *Ctenarytaina eucalypti* (Maskell, 1890) (blue gum psyllid)

This is a species from southeast Australia that has been introduced into many countries throughout the world. The first mention of *C. eucalypti* from Brazil is by Burckhardt et al. (1999), who reported it from Colombo – Paraná on seedlings of *E. dunnii*. Subsequently, it has also been detected in São Paulo, Santa Catarina and Rio Grande do Sul. Its geographical distribution, apart from its origin in Australia, includes Bolivia, Brazil, Chile, Colombia, Eire, France, Germany, Italy, New Zealand, Papua New Guinea, Portugal, South Africa, Spain, Sri Lanka, Switzerland, UK, Uruguay, and the USA (Burckhardt, 1998; Hodkinson, 1999; Durán & Urrutia, 2001; Burckhardt & Mühlethaler, 2003).

The adults of *C. eucalypti* (Fig. 1D) measure from 1.5–2.0 mm and have dirty whitish forewings with contrasting brown veins and a clear membrane which are normally folded over the body (Burckhardt et al., 1999). The body colour is usually dark brown to black (Burckhardt et al., 1999), with darker transverse stripes on the abdomen, both dorsally and ventrally. The antennae are yellow with dark apices of the individual segments. The compound eyes are dark brown and prominent. The legs are dark yellow. The female proctiger is longer and more slender in comparison with *C. spatulata*, with relatively acute apico-lateral peg setae and strongly curved valvula ventralis (Burckhardt et al., 1999). The female lays 20 to 100 eggs, normally in groups, on the leaf buds and in the axils of young leaves in nurseries or on young trees. Eggs are also laid in small fissures between the bud and the leaf pedicel. Several females may contribute to one egg mass. In summer, the incubation lasts about one week, whereas it is longer in the cold periods (Cadahia, 1980).

The first instar larvae are light yellow with red eyes and thick legs. There are thick setae along the margin of the caudal plate (Zondag 1982). The last instar larvae are yellow with dark patches. The eyes, antennae and wing buds are reddish-brown (Fig. 1E).

C. eucalypti has been observed in Brazil on many *Eucalyptus* spp., such as *E. globulus*, *E. maidenii*, *E. bicostata*, *E. dunnii* and *E. nitens*. Of particular importance are *E. dunnii* and *E. benthamii*, which are planted in temperate region on the south of Brazil where a high psyllid attack has been observed (Santana et al., 1999).

Hodkinson (1999) described the damage of *C. eucalypti*, including direct effects of psyllid feeding such as severe shoot dieback, leaf curl and leaf discoloration. A further factor damaging the plants is sooty mould growing on the honeydew, which is secreted in large amounts.

In Brazil, the development is continuous throughout the year, with several overlapping generations. All developmental stages have been observed to occur together at any particular time in the same population. All five larval instars excrete large amounts of honeydew and white waxy secretions (Fig. 1F).

4.3 *Blastopsylla occidentalis* Taylor, 1985 (eucalypt shoot psyllid)

Blastopsylla occidentalis originates from South and West Australia. Its geographical distribution is Argentina, Brazil, Cameroon, Chile, Hong Kong, Kenya, Mexico, New Zealand, Paraguay, South Africa and USA (Hodkinson, 1991; Burckhardt et al., 1999; Burckhardt & Elgueta, 2000; Hollis, 2004; Bouvet et al., 2005; anonymous, 2007; Tamesse et

al., 2011). According to the original description by Li (2011), *Blasopsylla barbara* from China may be a synonym of *B. occidentalis*.

The adults are small insects, measuring 1.5–2.0 mm. They have a yellow head and thorax with dark pattern, the head is as large as the thorax and strongly inclined relative to the longitudinal body axis, with short antennae (Fig. 2A). The forewings have brown veins and a grey membrane. The male terminalia are yellow, while those of the females are dark brown with a yellow base of the subgenital plate. The males are usually yellow, the females are darker coloured. The last instar larvae are yellow with a dark brown antennal tip; lacking humeral lobe on forewing buds or specialized setae; with 9-segmented antennae (Burckhardt & Elgueta, 2000; Meza & Baldini, 2001; Durán & Urrutia, 2001). *Blastopsylla* differs from other spondyliaspines by the very long posterior lobes on the basal segment of the male proctiger and often in the presence of a single spur on the metabasitarsus (Burckhardt & Elgueta 2000; Hollis, 2004). *B. occidentalis* can be easily separated from *Ctenarytaina* species by the lack of an outer apical comb of bristles on the mesotibia, and the apically curved vein Rs in the forewings (Taylor, 1990; Burckhardt et al., 1999; Burckhardt & Elgueta, 2000). Within *Blastopsylla*, *B. occidentalis* is similar to *B. moorei* from which it differs in the shape of the apical portion of the aedeagus, which is spherical rather than elongate and weakly curved as in *B. moorei*, and the fewer black setae on the apical portion on the inner surface of the paramere and the 4–6 dark sclerotised setae which form a line along hind margin, rather than a group of 5–7 as in *B. moorei* (Taylor, 1985). The females of *B. occidentalis* lay the eggs on the shoots, the leaf axils, on small branches and young leaves.

The larvae secrete large amounts of small wax covered globules containing honeydew and copious white flocculence (Fig. 2B), which enhances growth of sooty mould (Taylor, 1985; Meza & Baldini, 2001). The wax often sticks to the end of the larval abdomen.

B. occidentalis was observed for the first time in Brazil in Goiás in 1997 on hybrids of *Eucalyptus urophylla* and *E. grandis* (Burckhardt et al., 1999). Other hosts are *E. microtheca*, *E. rudis*, *E. gomphocephala*, *E. camaldulensis*, *E. microneura*, *E. nicholsii*, *E. spathulata*, *E. forrestiana*, *E. oleosa*, *E. rudis*, *E. tereticornis*, *E. saligna*, *E. globulus* and *E. nicholii* (Meza & Baldini 2001; Hollis, 2004).

Contrary to the two *Ctenarytaina* spp., *B. occidentalis* occurs in central Brazil, where the dry season is longer than in southern Brazil, with over four months without rain.

4.4 *Glycaspis brimblecombei* Moore, 1964 (red gum lerp psyllid)

Glycaspis brimblecombei (Fig. 2C), the red gum lerp psyllid, has an Australian origin and was introduced into the USA in June 1998 (Brennan et al., 1999). In 2000 it was observed in Mexico, in Chile in 2002 (Dahlsten, 2003), in Brazil in 2003, in Argentina in 2004 (Bouvet et al., 2005), in Ecuador in 2007 (Onore & Gara, 2007), in 2007 in Venezuela (Rosales et al., 2008), in Peru in 2008 (Burckhardt et al., 2008), in 2008 on the Iberian Peninsula (Hurtado & Reina, 2008; Valente & Hodkinson, 2009; Prieto-Lillo et al. in 2009) and in Italy in 2010 (Laudonia & Garonna, 2010; Peris-Felipo et al., 2011). In Brazil, *G. brimblecombei* was first detected in São Paulo and now it is wide-spread in the whole country in areas where its host is planted.

G. brimblecombei develops on various *Eucalyptus* spp., especially *E. camaldulensis* and *E. tereticornis* but also on *E. blakelyi*, *E. brassiana*, *E. bridgesiana*, *E. camphora*, *E. dealbata*, *E. diversicolor*, *E. globulus*, *E. mannifera*, *E. mannifera maculosa*, *E. nitens* and *E. sideroxylon* (Brennan et al., 2001; Hollis, 2004).

The eggs are laid in groups, usually in rows or circles (Fig. 2D). The larvae of *G. brimblecombei* (Fig. 2E) differ from those of the other three species discussed above, as they are not free-living. They live under a shield of wax, called lerp (Fig. 2F). Adults can easily be differentiated from *Blastopsylla* and *Ctenarytaina* spp. by the long genal processes, which are much longer than the vertex along the mid-line (Olivares et al., 2004; Burckhardt et al., 2008).

The damage of this species is similar to that made by the other species discussed above, but *G. brimblecombei* is a more aggressive exploiter of resources. There are reports of outbreaks in many South American countries where the species caused the death of the trees, resulting in serious production losses.

4.5 *Cardiaspina fiscella* Taylor, 1962 (brown lace lerp or brown basket lerp psyllid)

Cardiaspina fiscella is native to Australia, where it occurs naturally in the Australian Capital Territory, New South Wales and Victoria (Hollis, 2004). It uses as hosts *Eucalyptus botryoides*, *E. saligna*, *E. robusta*, *E. grandis* (Collet, 2001a), *E. camaldulensis*, *E. blakelyi* (Collet, 2001b), *E. globulus* and *E. tereticornis*. According to Withers (2001), 57 insect species originating from Australia have been introduced in New Zealand, among them, *C. fiscella*. This species was detected in New Zealand in 1996 and it quickly diffused to most of the North Island, with severe infestations, successive defoliation, dieback and general decline of plantings of *Eucalyptus botryoides* and *E. saligna*. According to Berry (2006), *C. fiscella* is the only introduced species of Australia that has become a significant pest on *E. botryoides*, *E. grandis* and *E. saligna* in New Zealand.

There are many species of *Cardiaspina* using eucalyptus as a host, among which *C. fiscella* is one which most often reaches high populations (Campbell, 1992). Adults of this Australian psyllid species are 3.4 mm in length, from head to wing tip. They have a short, more robust body than the other species mentioned previously. Antennae are almost equal to width to the head. Legs are stout with two very small claws. The general colour is light brown; the head straw coloured; the thorax bears several medium brown patches; the abdomen is brownish black, with a yellow or red caudal margin on each segment. The forewings are transparent with uniformly light brown veins (Fig. 3A).

The larvae (Fig. 3B) build very elaborate lerps, which are shell-shaped (Fig. 3C), consisting of a tangled lattice, usually on the dorsal surface of the leaves (Hollis, 2004). Dimensions are approximately 4.1 mm from hinge to apex, and approximately 5.4 mm across. General colour is light brown, darker near the hinge with a darker band where the ribs begin to fan out. It is moderately convex. Larvae can move freely underneath the lerp and can sometimes be seen moving on the undersides of leaves outside of the lerp (Appleton, 2009). The larvae of *C. fiscella* have glands that secrete wax filaments to produce the lerp. Larvae of all *Cardiaspina* spp. form fan-shaped basket lerps, with unique characteristics for each species. Often, necrosis on foliage of mature leaves occurs beneath the lerp (Fig. 3D, E), as can be found on many eucalypt species, especially of *E. camaldulensis* and *E. blakelyi* (Collet, 2001a).



Fig. 2. *Blastopsylla occidentalis* (A - adult, B - colony of larva); *Glycaspis brimblecombei* (C - adult, D - eggs, E - larvae, F - lerps on leaf).

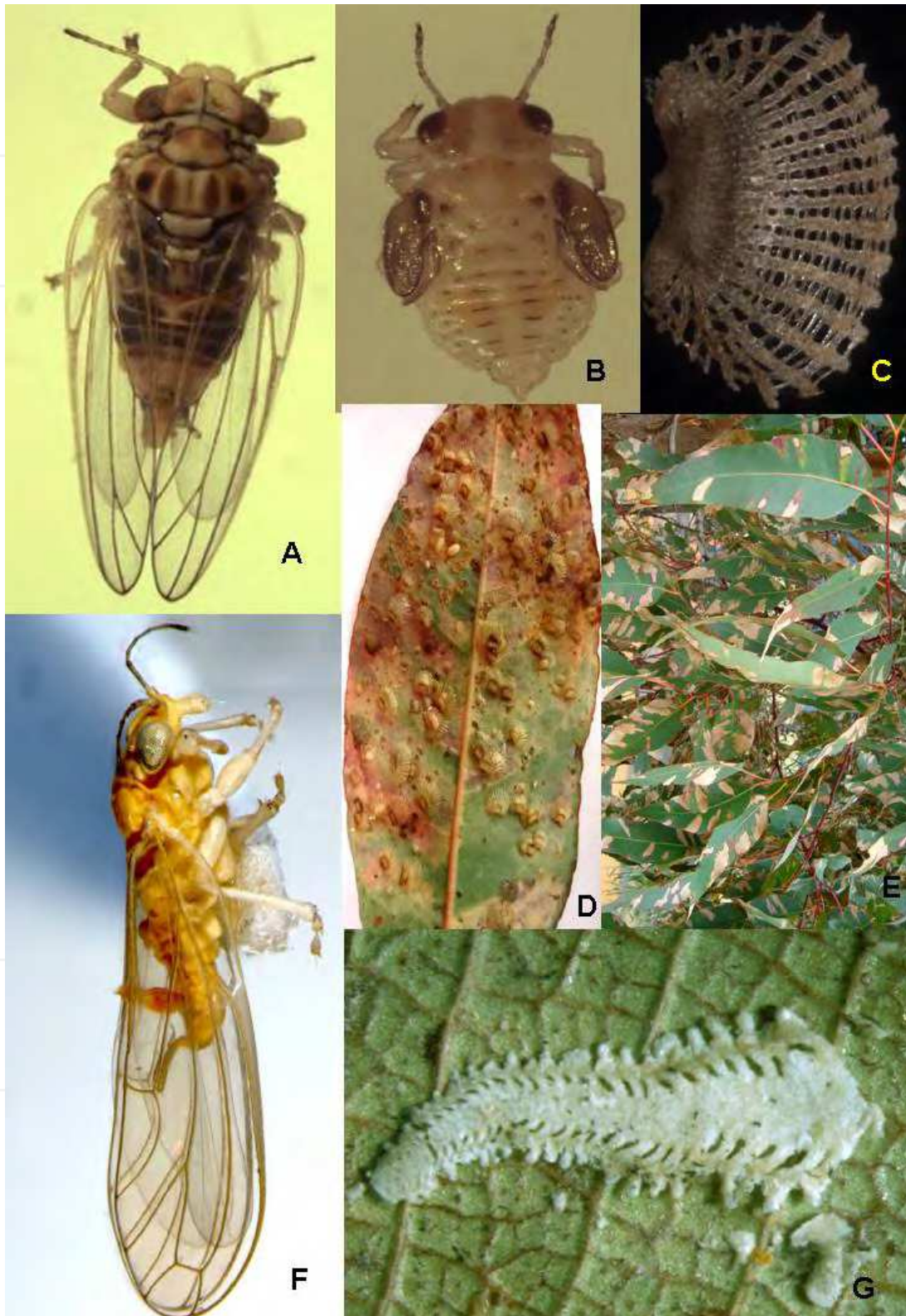


Fig. 3. *Cardiaspina fiscella* (A - adult, B- larva, C - lerp, D, E - damage on leaves); *Eucalyptolyma maideni* (F - adult, G - lerp on leaf).

4.6 *Cryptoneossa triangula* Taylor, 1990 (lemon gum psyllid)

Cryptoneossa triangula was described from *Corymbia citriodora* and *C. maculata* trees collected in the Australian Capital Territory and New South Wales (Taylor, 1990). This species is morphologically similar to *C. minuta* and *C. leptospermi* and derives its name from the triangular shape of the parameres. Adults have a general ochraceous to brown colour and the vertex has a narrow black margin in some specimens. The forewings are relatively longer and narrower than those of *C. minuta* and the marginal cell cu_1 is not as flat as in *C. leptospermi*. Males of *C. triangula* are 1.8 to 2.2 mm length. The head bears spheroid genal processes and anterior margins of vertex expanded on each side of median ocellus; anterior orbital lobes small, conical. The basitarsus has two black spurs. Females are 2.3 to 2.6 mm long with rounded anterorbital lobes (Taylor, 1990).

In August 2000, this psyllid was discovered on California's lemon-scented gum (*C. citriodora*) and spotted gum (*C. maculata*) trees at Disney Resort and surrounding areas of Anaheim, California. The lemon gum psyllid (*C. triangula*) is a free-living psyllid causing leaf damage and inducing leaf drop, which may stress trees and make them susceptible to fatal attack by other insects. The psyllids also produce sticky honeydew, which soils the ground, cars and sidewalks (Dahlsten, 2001; Daane & Paine, 2005).

4.7 *Eucalyptolyma maideni* Froggatt, 1901 (spotted gum lerp psyllid)

Eucalyptolyma maideni was described from *Eucalyptus* spp. and later redescribed by Taylor (1987) from *C. citriodora*, *C. gummifera* and *C. maculata*, with records in New South Wales, Australian Capital Territory and South Australia. The adults have general bright green colour tinged with yellow (Fig. 3F). The lerp is white, corniculate, with lacinate margins (Taylor, 1987). According to Morgan (1984), this psyllid is widespread in eucalypt forests from Queensland and South Australia to Tasmania. It is trivoltine and prefers fully mature leaves upon which to feed, oviposit and develop.

This psyllid was introduced in USA in 2000 and collected from *C. citriodora* in Los Angeles, California. Since then, it was also discovered near Anaheim (at Disney Resort) and heavy infestations have been reported from many locations within Los Angeles, Orange County and San Diego. Although this insect does not cause the death of the plants, it is considered to be an ornamental pest of lemon scented gum and spotted gum in California. Larvae build a flattened and elongated triangular lerp (Fig. 3G) and produce a copious amount of honeydew which soils the ground beneath trees, similar to that mentioned for *C. triangula*, where a blackish sooty mould grows (Garrison, 2001).

5. Integrated Pest Management (IPM)

The integrated management of the psyllids should start with monitoring, which should be continuous, with more attention being paid in peak periods. The monitoring of the psyllids can be done by installing sticky traps or by manual sampling. These should be run continuously and at regular intervals. Yellow sticky traps are the best way to monitor psyllids infesting eucalypts. Adult psyllids and psyllid parasites are attracted by the yellow colour and become stuck to the surface. The traps should be inspected once a week and the

number of adult psyllids and their parasites should be counted and recorded (Paine et al., 2007).

Adult psyllids can also be monitored by shaking or beating plants over a collecting sheet to knock them onto the collecting surface, where they can be easily seen and counted. The sample should be taken about once a week during the season of new plant growth, when adult psyllids are expected (Dreistadt & Dahlsten, 2007).

Through such monitoring, it is possible to determine the moment of population peak, the occurrence of natural enemies and other factors that affect the insect population. In an Integrated Pest Management Programme (IPM), monitoring the pest's development is one of the main components, which uses different techniques to quantify the population and predict outbreaks of the pest. Besides, it can be also used to determine the geographic distribution of the pest, to detect a risk to the area before any damage actually occurs and to determine the effectiveness of the control treatment.

5.1 Biological control

The use of parasitism is a major component of psyllid IPM, with several biological control programmes having been successfully carried out for different species of introduced psyllid. A biological control programme of *C. eucalypti* was supported by the University of California IPM project. The parasitoid *Psyllaephagus pilosus* (Hymenoptera: Encyrtidae) was collected in Australia, reared at UC Berkeley and released in California. The parasitoids quickly established in the release sites, and sampling in 1994 revealed parasitism rates of 50–100%. By 1995, the parasitoids had become broadly distributed throughout many parts of the State. An economic analysis of the benefit to the cut-foilage industry alone indicated that the biological control programme generated a benefit-cost ratio ranging from a minimum of 9:1 to a maximum of 24:1, based solely on elimination of pesticide treatments (Dahlsten et al., 1998a). A similar IPM programme was adopted to manage the populations of the lerp psyllid *G. brimblecombei* in California (Paine et al., 2007).

In Brazil, in the end of 2000, beginning of 2001, a sudden population decrease was observed, because of the hymenopterous parasitoids which attacked *C. eucalypti*. The parasitoid was identified as *Psyllaephagus* sp. (Hymenoptera: Encyrtidae), the same genus which has been introduced into many European and American countries for the biological control of *C. eucalypti* (Santana et al., 2002). The parasitoids of *C. eucalypti* (*P. pilosus*) and *G. brimblecombei* (*P. bliteus*) were introduced accidentally together with their hosts in Brazil (Santana et al., 2002; Berti Filho et al., 2003). These parasitoids adapted and dispersed over the whole Brazilian territory. Now they can be found in practically all the areas where the pest is present. The natural control of these psyllids has been successfully facilitated using these specific parasitoids (Santana & Burckhardt, 2007).

The decrease of the *G. brimblecombei* population observed in São Paulo, Brazil in the end of spring, beginning of summer in 2003, was attributed to the rainfall and certainly because of the presence of parasitoids and predators (Fig. 4). The parasitoid *P. bliteus* (Fig. 4 A, B) was detected in the same year of introduction of *G. brimblecombei* in São Paulo State, Paraná and Minas Gerais. With the detection of this parasitoid, it is expected that the population of the psyllid will also stabilize (Santana et al., 2003b). Now, the management of the pest and its natural enemies is established.

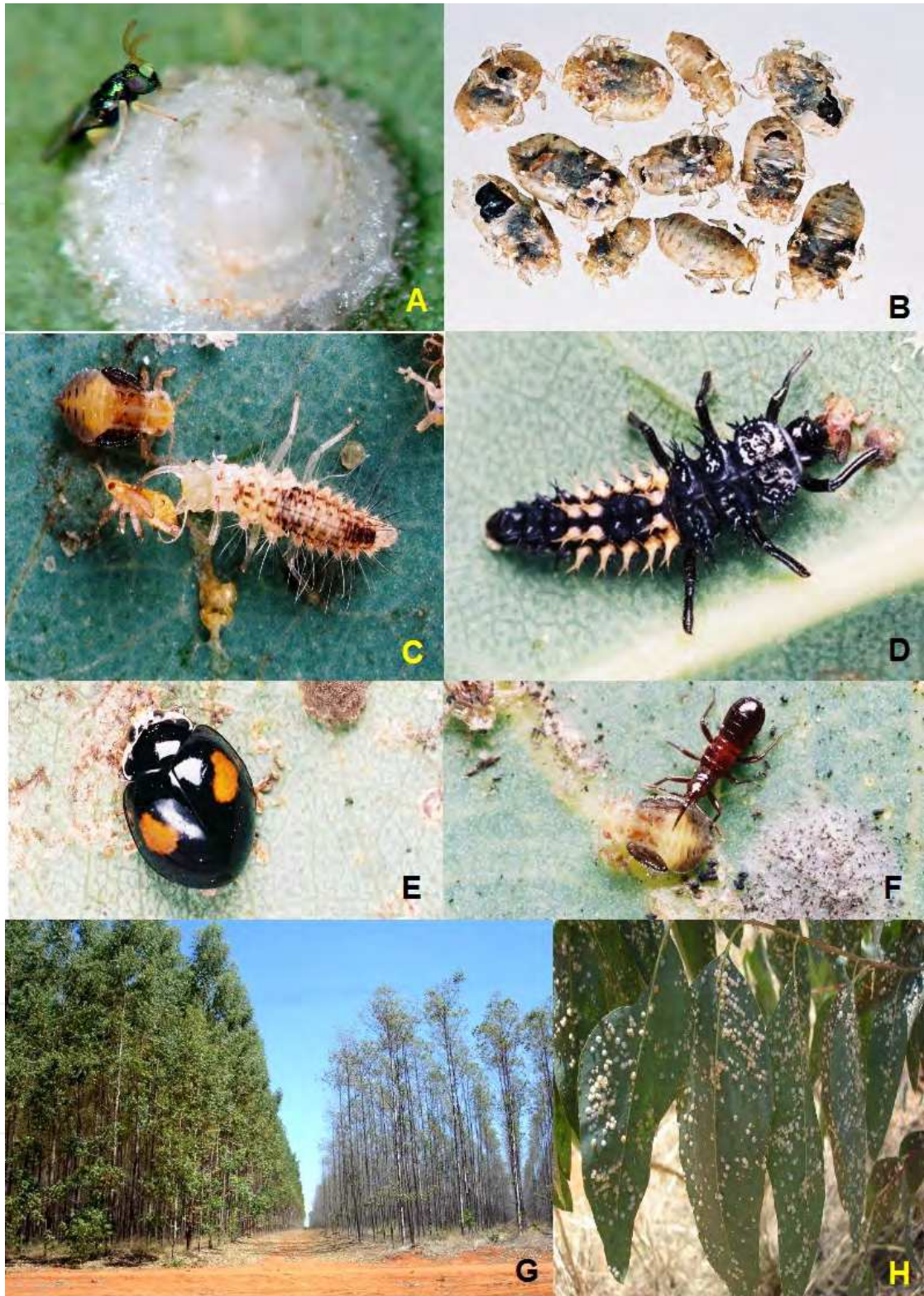


Fig. 4. Psyllid IPM. A, B - Parasitoid *P. bliteus*; C-F - predators, G - clone plantation: *G. brimblecombei* resistant (left) susceptible (right); H - detail of infestation on susceptible clone.

Withers (2000) reported the occurrence of *Psyllaephagus gemitus* in *C. fiscella*. According to this author, the health of eucalypt trees in the North Island of New Zealand can be expected

to improve as populations of *C. fiscella* continue to be killed by *P. gemitus*, a nymphal parasitoid. This same parasitoid, *P. gemitus*, was tested in 1997 as a possible biological control agent for *C. fiscella* by entomologists funded by the New Zealand Farm Forestry Association. A parasitic microwasp associated with brown lace lerp (*C. fiscella*) has been recorded from New Zealand. This microwasp, *Coccidoctonus psyllae*, is a hyperparasitoid and its presence will probably contribute to an increase in brown lace lerp populations (Berry, 2006).

The eucalypt psyllids are also attacked by many predators, including the ladybird beetles (*Cycloneda sanguinea*, *Olla v-nigrum* (Fig. 4C), *Hippodamia convergens*, *Eriopsis connexa* and *Harmonia axyridis* (Fig. 4D), the green lacewings (*Chrysoperla* spp.) (Fig. 4E), syrphid flies, pirate bugs (*Anthocoris* sp.) (Fig. 4F) and spiders (Santana, 2003; Santana et al., 2004). Although predators do not provide complete biological control, they can reduce psyllid abundance. Whenever possible, management efforts should be selected that have less adverse effects on these beneficial species (Paine et al., 2007). Santana (2003) observed the following potential natural enemies for *C. spatulata*: *Coccinella ocelligera*, *Curinus coeruleus*, *Cycloneda pulchella*, *Cycloneda sanguinea*, *Eriopsis connexa*, *Harmonia axyridis*, *Hyppodamia convergens*, *Hyperaspis* sp., *Scymnus* (*Pullus*) sp. and *Olla v-nigrum* (Coleoptera: Coccinellidae), *Chrysoperla externa* (Neuroptera: Chrysopidae); *Allograpta exotica*, *Pseudodorus clavatus*, *Syrphus phaeostigma* (Diptera: Syrphidae), as well as spiders and the fungus *Verticillium lecanii*. The same predators observed for *C. spatulata* also attack *B. occidentalis*, including Syrphidae, Dolichopodidae (both Diptera), Chrysopidae (Neuroptera) and Coccinellidae (Coleoptera) (Santana & Burckhardt; 2007).

Azevedo and Figo (1979) list the following natural enemies of *C. eucalypti* in Portugal: *Syrphocotonus abdominalis* (Hymenoptera: Ichneumonidae); *Haematopota ocelligera* (Diptera: Tabanidae); *Sphaerophoria scripta*, *Meliscaeva cinctellus*, *Pipizella* sp., *Eumerus* sp. (Diptera: Syrphidae); and *Bradysia* sp. (Diptera: Sciaridae). The predator complex feeding on *C. eucalypti* includes hoverfly larvae, ladybirds, lacewings, anthocorids and spiders (Hodkinson, 1999). According to Zondag (1982), *C. eucalypti* is frequently attacked by a small black wasp in New Zealand. In Tasmania, a small ladybird (*Cleobora mellyi*), used to control a beetle, has been observed feeding on larvae and eggs of psyllids, showing a high potential to control *C. eucalypti*.

5.2 Plant resistance

The search for tolerant or resistant plants has been an economically viable alternative to contain populations of these insects in large plantations. Tolerance varies among eucalypt species and location of plants. Prevention of planting susceptible species is the best way to avoid damage (Dreistadt et al., 2007). According to White (1970), who studied aspects of the life history of *Cardiaspina densitexta*, the physiological and physical characteristics of plants influence the selection of hosts.

Brennan and Weinbaum (2001a) studied the performance of psyllid adults on leaves of *E. globulus* and noted that the epicuticular wax of juvenile leaves plays an important role in resistance to *C. spatulata* and *G. brimblecombei*; these species tend to avoid more waxy leaves. Brennan and Weinbaum (2001b) suggested that the tarsi of *C. eucalypti* are more adapted for adhering to the epicuticular wax-coated surfaces than those of the others two psyllid

species. Continuing these studies, Brennan and Weinbaum (2001c) concluded that the epicuticular wax on juvenile *E. globulus* leaves reduces stylet probing by *C. spatulata* and *G. brimblecombei* and this psyllid avoids oil glands on the leaves.

In breeding programmes for improving physical and chemical properties of plants, all aspects related to resistance should be analysed. In Brazil, where most eucalypt plantations are clonal, the forestry companies already have some materials selected in the search for resistance (Fig. 4G, H).

In order to verify the preference of *C. spatulata* for laying eggs and feeding, Santana et al. (2010) carried out a green-house trial on 19 *Eucalyptus* species, one *Eucalyptus* hybrid (Cambiju), three *Corymbia* species and four native Myrtaceae species (*Hexaclamys edulis*, *Plinia edulis*, *Plinia trunciflora* and *Psidium* sp.). As a result of this trial, they found that the largest populations of *C. spatulata* were observed on *E. robusta* and *E. pellita*. *E. grandis* and *E. resinifera*, however, presented the largest number of plants with symptoms of damage. *E. cinerea*, *E. cloeziana*, *E. dunnii*, *E. benthamii*, *E. nitens*, *E. viminalis*, *E. pilularis*, *E. camaldulensis* and *E. dunnii* did not suffer infestations of *C. spatulata*. Among the *Corymbia* species, eggs of *C. spatulata* were only observed on *C. citriodora* with adult leaves. None of the native Myrtaceae had eggs or larvae of *C. spatulata*.

Camargo et al. (2009) evaluated the resistance of different clones of *E. camaldulensis* to attack by *G. brimblecombei* and observed that the largest mean for eggs and larvae were observed on commercial clones 7, 58, 62, 10 and 6. The same ones did not differ statistically, all being considered as highly susceptible to the attack of the red gum lerp psyllid. The clones GG100, 36, 2, I042 and I224 did not differ statistically to each other and they were classified as resistant to psyllid attacks. Clone 19 presented an intermediate average among the two groups, being classified as susceptible. Clone 58 is known as one of the most productive in the Cerrado region of Minas Gerais but, because of its high susceptibility to red gum lerp psyllids, companies are being discouraged from planting it in areas of greatest occurrence of this pest.

5.3 Cultural control

According to White (1986), the decline of some eucalypt forests in Australia is primarily caused by changes in rainfall patterns, which induce physiological stress in plants. In physiologically stressed plants, the amount of nitrogen available as a food source for psyllids is higher. The eucalypts are damaged more by the psyllids as the increase in nitrogen content increases the chance of survival of the psyllids and their populations grow rapidly (White, 1969). The requirements of insects for mineral salts is not well defined but it is known that they are very important for the ionic balance and cell membrane permeability of insects, acting as activators of enzymes (Panizzi & Parra, 1991). Thus, different types of fertilizers can affect insect populations positively or negatively. Some nutrients are very important in plant-insect relationships and have been thoroughly researched, such as nitrogen (White, 1969), magnesium (Santana et al., 1999), silicon (Camargo et al., 2011) and others.

To minimize plant stress, certain cultural practices have been recommended as a measure to strengthen the plant and provide higher resistance to psyllids. As excess nitrogen in the leaves leads to an increase in insect populations, a balanced fertilisation and irrigation in the

dry season is recommended to avoid the concentration of this nutrient in the leaves (Garrison, 2001).

Although silicon is not considered an essential element for plants, it is absorbed and is involved in the formation of structures of defences such as trichomes and spines. It also contributes to greater leaf toughness by forming polymers (crystals) that are immobilised in the leaf tissue (Camargo et al., 2011). Thus, the application of industrial ashes rich in silicates has been recommended for commercial planting of eucalypts in regions poor in this element.

5.4 Chemical control

Adult psyllids should be monitored before damage becomes evident and the numbers of adults present should be recorded on a weekly basis. During subsequent seasons control action should be taken, if necessary, when populations or damage approach the levels that were previously identified to be intolerable. The foliar damage is primarily caused by larvae, but sprays are generally aimed at killing eggs or newly hatched larvae before the damage occurs, which is why the adults should be monitored. Therefore, a decision to spray should be based on the numbers of adults infesting the plants several weeks before larval damage becomes intolerable (Dreistadt et al., 2007).

The overlapping generations of the psyllids makes chemical control even harder because it requires successive spraying of insecticides. This increases production costs and requires additional work, which demands the definition of a management strategy to be more critical. Usually the control is made through IPM, mainly biological control using predators or parasitoids. In most cases the chemical control is not recommended because it is expensive, less efficient and may cause environmental damage (Santana & Burckhardt, 2007).

There are, however, instances when chemical control is necessary. When *C. eucalypti* was introduced into the USA, it caused up to 30% of production loss in commercial plantations of *E. pulverulenta* in California (Dahlsten et al., 1998b), making it necessary to apply chemical control. Nevertheless, considering the fast dispersal and establishment of this psyllid, eradication methods are not effective and chemical control is expensive and efficient for a short time. Its ready adaptation to tropical climatic conditions, its fast dispersal and the large areas planted with eucalypts suggest that this psyllid should be controlled by a programme of Integrated Pest Management, based on the management of the pest and its interaction with the ambient environment and other organisms.

6. Modelling Psylloidea dispersion

Invasive species can be introduced accidentally by humans or by natural dispersal. To provide the right conditions for the occurrence of a particular species, it is necessary to understand the factors that circumscribe their niche, such as abiotic conditions that define the physiological limits to the persistence of species, biological factors that influence the survival of populations (which may be negative in the case of competition, predation and parasitism, or positive, in the case of mutualism), and dispersal ability, which reflects what sites are accessible to individuals of a species (Soberón & Peterson, 2005).

Far from home and their environment and free of predatory and competitive processes, invasive alien species have favorable conditions for expansion and occupation, especially if its space or ecosystem has been altered by successive processes of human interventions. Possible areas of risk of introduction, spread and future distribution of invasive species are often estimated by bioclimatic modelling, also known as ecological niche modelling.

The process of modelling the potential geographic distribution of biological species can be summarized in the following steps: 1) a set of points of occurrence (georeferenced) is combined with a set of environmental variables, creating a niche group of points. Each point in this niche is formed by the values assumed by the environmental variables at each point of occurrence; (2) a modelling algorithm is used to create a niche model from the set of points niche; and (3) the model of niche created by the algorithm is applied on a certain geographic region, taking into account the same environmental variables used to create this niche model (Rodrigues, et al. 2010). Work is currently underway to model the potential distribution of introduced psyllids in Brazil so that plantations can be planned and managed in order to minimize the threat from these pests.

7. Conclusions

Jumping plant-lice are a major threat to large scale commercial eucalypt plantations. Of the approximately 350 described Australian species, over 250 are associated with eucalypts (Hollis, 2004). Of these, only seven species have been introduced into other continents and four have become economically important pests. However, there is large potential for other Australian spondyliaspidine species to be accidentally or intentionally exported into other continents. Improving the existing taxonomic base would help in the rapid recognition of new spondyliaspidine introductions. Incidentally, two of the four major psyllid pests on eucalypts have been described, in part, on the basis of non-Australian material (*Blastopsylla occidentalis* and *Ctenarytaina spatulata*). *Ctenarytaina peregrina*, which is almost certainly of Australian origin, is currently known only from Europe. A detailed taxonomic revision of *Ctenarytaina* is particularly important if we are to understand the threat from members of this genus.

Of the eucalypt species observed as hosts of *C. fiscella*, *E. grandis* and its hybrids are particularly important for Brazilian national forestry. Besides these, other species such as *E. camaldulensis* and *E. urophylla* are also susceptible and they are planted over large areas, or are the base for the production of clones. These species are already attacked by the red gum lerp psyllid (*G. brimblecombei*) and the introduction of one more pest can make the use of some genetic materials of great productivity unviable. For all these reasons, the acquisition of good taxonomic knowledge, and the amassing of control tools for incorporation into IPM programme are essential if Brazilian forestry is to be protected from this important group of insects.

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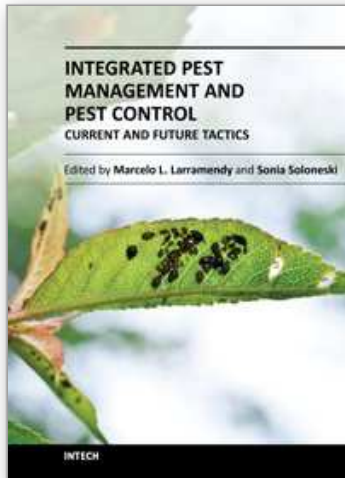
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