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# Insects and Other Animals in Tropical Forests

Martin R. Speight

## Contents

Vertebrates .....	2608
Invertebrates Other Than Insects .....	2609
Insects .....	2609
Insect Groups .....	2609
The Reasons for Insect Pest Outbreaks in Tropical Forestry .....	2627
Climate Change .....	2627
Ecological Pest Management .....	2629
Monocultures .....	2629
Site Choice .....	2630
Pest Reservoirs .....	2631
Exotic Pests and Invasions .....	2631
Quarantine and Forest Health Surveillance .....	2632
Tree Susceptibility and Resistance .....	2632
Stand Management .....	2634
Chemical Control .....	2635
Insecticides .....	2635
Pheromones .....	2636
Biological Control .....	2637
Predators and Parasitoids .....	2637
Pathogens .....	2639
Integrated Pest Management .....	2641
IPM Examples .....	2642
Future Trends .....	2648
References .....	2648

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**Abstract**

Insects that cause economic damage to tropical trees can be classified into various categories according to how they feed. Defoliators remove leaf material, reducing tree growth by reducing photosynthetic area, sap feeders remove phloem or xylem sap, competing with the tree for its own products, whilst borers tunnel into bark or timber killing trees by girdling or damaging timber by creating holes or introducing stains. Insect pest outbreaks can occur for a variety of reasons. Primary pests such as sap feeders and defoliators may render trees susceptible to secondary pests such as the borers. In many cases, trees are susceptible to insect damage by virtue of being planted in locations, soils, and climatic conditions which are unsuitable for them; stressed trees are very often more likely to suffer serious pest attacks than healthy ones. Resistant trees must be grown if possible in sites to which they are suited. In addition, insect population densities may rise to damaging levels because regulation by natural enemies is reduced or missing altogether due to trees being grown in exotic locations, to insects invading from other regions or forest activities such as the removal of native vegetation or the misuse of pesticides. Insect pest management should always in the first instance be thought of as a preventative measure, since pest control, once insects start to cause significant losses, is frequently difficult if not impossible on large plantation scales. Monitoring of pest populations followed by predictions of damage intensities must be used to determine pest management tactics.

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**Keywords**

Defoliator • Sap feeder • Borer • Coleoptera • Lepidoptera • Hemiptera • Isoptera • Ecological control • Biological control • Chemical control • Monitoring • Integrated pest management

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**Vertebrates**

Mammals and birds can exert considerable impact on forest trees. Grazing on young trees by deer and other ungulates such as cattle can cause heavy losses, in terms of both growth retardation and tree mortality. Bigger trees can suffer severe bark stripping by, for example, elephants and buffalo. Even humans can cause damage by branch lopping, bark removal, and the collection of litter for mulch which deprives stands of nutrients to recycle. Mammal control is problematic; fences are too expensive and not very effective, whilst chemical deterrents are usually impractical. Domestic livestock may require more careful management by villagers. Damage to forests by birds is most prevalent in seed orchards where again control is difficult.

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## Invertebrates Other Than Insects

Mites, barnacles, and nematodes can be pests of tropical trees. There are more nematodes per unit area of forest soil than any other multicellular animal. Those that may be pestiferous can be grouped into three categories: (1) those feeding on aerial plant parts, (2) those feeding on mycorrhizal symbionts, and (3) those feeding directly on or in the roots. Wounding of the tree roots by nematode feeding may also allow ingress of pathogenic fungi. The root-knot nematodes, *Meloidogyne* spp., has larvae which penetrate root cells, causing enlargement and swelling, often resulting in wilting and retarded growth of the host. The distribution is broad; the genus is a problem in nurseries from Malaysia and Papua New Guinea to Egypt, Zimbabwe, and Central America, feeding on species of *Leucaena*, *Casuarina*, and *Eucalyptus*, for example. As with many insects, nematode control is possible in nursery situations, but is more difficult later.

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## Insects

The majority of insect species are herbivorous. Most, however, do not consume an undue quantity of plant material, and, indeed, plants have evolved defenses, both chemical and physical, to reduce the severity of this feeding. Certain groups of insects are, however, notorious in tropical forestry as potential or actual pests, causing a great deal of increment loss, deformation and mortality. The following account briefly describes some of the more widespread groups and provides, where known, details of their impact to forest crops. It must be emphasized that quantitative impact studies are sadly lacking in many cases; a great deal more fundamental research is required to provide data which forest managers can use in planning and decision making.

## Insect Groups

### Isoptera: Termites

It must be stressed at the outset that termites are a vital component of tropical ecosystems. They perform the essential task of nutrient recycling and are thus extremely beneficial (Varma and Swaran 2007). However, some species feed on living trees and are amongst the most serious insect pests of tropical forestry. Termite attacks may be observed in older, established trees in plantations, and it is tempting to attribute the death of these trees to termites, especially when active galleries are found in the wood. However, primary attack of healthy trees is rare and other reasons for debilitation should be sought. In most cases, termite problems only arise when the trees are already stressed, though Kirton and Cheng (2007) did find termites attacking healthy young dipterocarps in Peninsular Malaysia. Damage

to the roots or aerial parts caused by mishandling at the pricking out or nursery stage, wounding due to excessive brushing, pruning, or browsing mammals can all predispose trees to termite attack. Fungal decay is often found to be a primary associate with termite abundance. In Malaysia, for instance, *Acacia mangium* trees with termite galleries up the center were found to be infected with butt rot fungi in almost all cases. In general terms, the bark of a tree, when intact, forms an effective defence against termite workers foraging in earthen tunnels up the trunks and usually the wood underneath remains unattacked. Similarly, stands of *Araucaria cunninghamii* in Penang, Malaysia, were found to be commonly infested by wood-boring termites (Jasmi and Ahmad 2011) but mainly in stumps and moribund timber. There is no economically viable way to control termite attacks to established trees; only prevention is possible, which usually involves the selection of a resistant tree species, or the removal of various predisposing factors such as those mentioned above. Much more common and economically serious throughout the tropical world are termite attacks to newly transplanted trees. Data vary tremendously, but mortality levels can be as high as 80–100 %. The species of tree thus affected vary, but experience shows that exotics such as eucalypts and pines are more heavily attacked than indigenous ones (Wardell 1987). Trees in the nursery and first year after planting seem to be the most susceptible (Kumar and Thakur 2011). Genera of termites responsible for these attacks vary from country to country, but *Coptotermes*, *Eurytermes*, *Microtermes*, and *Odontotermes* are particularly well known. Typically, termites attack the tap root of transplants a few centimeters below the ground (Fig. 1), severing the roots and causing dumbbell-shaped swellings on the main stem at ground level. Various ecological systems for reducing this damage have been suggested, but as with established trees, the only reliable methods include the choice of resistant species of tree or the use of persistent soil insecticides (Mitchell 2002). More recently, entomopathogenic fungi (Nagaraju et al. 2013) and bacteria (Nagaraju et al. 2012) have been trialed with limited success. It is important to note that several other factors can affect the survival of transplanted trees, such as planting stress, attack by insects such as moth and butterfly larvae or crickets in the nursery prior to planting out and also after the event, fungal attacks such as damping off and even grazing by mammals. Evidence of termite attack to the roots of sickly looking transplants must be sought. It must be remembered that losses of up to 20 % or so can usually be tolerated and the gaps filled by beating up some while after initial planting.

### **Hemiptera: Sap Feeding Insects; True Bugs**

All the Hemiptera have mouthparts specially adapted for piercing the outer surface of hosts and feeding on the liquid contents, which in the case of herbivorous species, is usually phloem or xylem sap. In doing so, the tree is deprived of photosynthetic products, which results at minimum in localized cell death or deformation, and at maximum in increment loss or even whole tree mortality. The order Hemiptera is conventionally split into two suborders – the Heteroptera and the Homoptera. The former group contains insects such as capsid bugs which

**Fig. 1** Termite damage to nursery tap root (Malaysia)  
(Photo: Martin Speight)



feed mainly on the contents of leaf epidermal cells, causing yellowing and occasional deformation.

Much more important are the Homoptera, which contain psyllids, aphids, scale insects, bronze bugs, and all notorious pests of tropical forestry. The Psyllidae variously known as plant or leaf hoppers, jumping plant lice or lerp insects, are typified by the leucaena psyllid, *Heteropsylla cubana*, (Fig. 2), the gall psyllid, *Phytolyma lata* (Fig. 3), and the red gum lerp psyllid, *Glycaspis brimblecombei* (Fig. 4). *Heteropsylla cubana* is fairly host plant specific, and is a major pest of *Leucaena* species, especially the so-called agroforestry “wonder tree,” *L. leucocephala*. This tree, which is a native of Central America, has been established in many parts of the tropical world, including the Pacific, south and south-eastern Asia, Africa, and South America (Brewbaker 1987). The pest is now widespread and extremely serious in many countries in which the tree is exotic, including Fiji, Hawaii, Taiwan, Thailand, India, and Nepal. It is present in Africa, and has become a serious pest in Kenya (Ogol and Spence 1997), Cameroon (Alene et al. 2012), and Zimbabwe (Matimati et al. 2009). Nymphs and adults feed on the stems and leaves of the host, causing immense damage which includes defoliation, deformation, stunting, and dieback; young trees may be killed and the fuelwood and fodder production drastically reduced.

**Fig. 2** *Leucaena* psyllid,  
*Heteropsylla cubana* (Nepal)  
(Photo: Martin Speight)



**Fig. 3** Gall psyllid,  
*Phytolyma lata* (W. Africa)  
(Photo: F. Brunk CIRAD)



*Phytolyma lata* attacks the leaves of young *Milicia* spp. (iroko) in parts of West Africa especially when the seedlings are planted in large openings and clearings (Nichols et al. 1999b), whereas *Glycaspis brimblecombei* is now a very widespread pest of eucalypts. Originating in Australia, this psyllid is now a serious problem in Brazil (Pereira et al. 2008), India (Ramanagouda et al. 2011), Morocco (Maatouf and Lumaret 2012), Chile (Huerta et al. 2011), Argentina (Ganci and Lanatti (2011), Mauritius (Hollis 2004), Venezuela (Julio Rosales et al. 2008), Peru (Burckhardt et al. 2008), in fact pretty much everywhere that *Eucalyptus* is grown commercially these days. In Brazil at least, the preferred hosts are *Eucalyptus camaldulensis* and *E. tereticornis*, on which the psyllid causes leaf deformation and curling as well as spoiling by the growth of sooty molds on the honeydew produced by the pest (de Queiroz et al. 2012). At the moment, biological control by an Australian parasitoid, *Psyllaephagus bliteus* (Ferreira Filho et al. 2008) has little effect.

**Fig. 4** *Eucalyptus* lerp psylliids (Australia) (Photo: Martin Speight)



**Fig. 5** Damage to *Cupressus* by cypress aphid, *Cinara* spp. (Malawi) (Photo: Martin Speight)



Aphids and scales are universal pests of all types of agricultural and forest crops. They are specialized for optimum reproductive rates, and host finding and exploitation and can be considered as quintessential herbivores. They compete with host trees for the latter's own photosynthetic products, and are thus able to exert extensive increment losses. For example, studies on scale insects in the UK have shown that infested trees suffer growth reductions as measured by shoot elongation of over 90 % when compared with pest-free trees; root biomass is also affected (Speight 1991). The tropical aphid *Cinara cupressi* (Fig. 5), a major problem in various parts of Africa and now South America (Montalva et al. 2010), also causes severe increment losses and even death in plantations of cypress. Other aphid species feed on tree stems, thereby causing changes in wood properties. The black pine aphid, *Cinara cronartii*, in South Africa, causes the formation of compression wood in its host, *Pinus taeda*, thus rendering the timber useless, with the potential for huge financial losses.

### **Orthoptera: Crickets, Grasshoppers, and Locusts**

Tropical forest nurseries often report quite serious defoliation of young trees by a large variety of rather generalist insects which chew at the leaves, stems, and more rarely, the roots. Bush crickets (Tettigonidae) and grasshoppers (Acrididae) can be distinguished by virtue of the very long antennae possessed by the former. Since they are generalists, wild vegetation or even agricultural crops around forest nurseries can act as reservoirs for these pests which periodically invade. Young transplants can also be killed by true crickets (Gryllidae) which live in tunnels, emerging to sever young trees near ground level. The effects of crickets can sometimes be mistaken for termite attack, at least in terms of gaps in a line of transplants.

### **Lepidoptera: Butterflies and Moths**

Of all pests of tropical forests, the Lepidoptera are probably the best known. Their activities range from leaf feeding (defoliation), to stem and wood boring, and all stages of trees may be attacked by one species or another.

- (a) **Defoliators.** Since trees rely on their leaves for photosynthesis and subsequent growth and reproduction, anything which removes leaf material will have direct consequences on the tree's future increment, vigour, and even survival. As well as direct increment losses, a whole range of other problems may manifest themselves. Trees can normally withstand some degree of defoliation; in fact, natural forests can be expected to suffer considerable defoliation levels from many groups of insects including the Lepidoptera. Tolerance is a product of insect-plant co-evolution, but very high levels or repeated bouts of defoliation can cause severe and unrecoverable depredations. Furthermore, since most trees have defences against shoot and stem-boring insects based on simple sap or resin pressure systems, removal of the transpiration stream produced by the leaves also reduces this defence system, rendering the trees very susceptible to so-called secondary pests such as wood-boring beetles (see below).

The impact of defoliators can often reach considerable proportions, but is rarely quantified. A defoliated stand of trees often appears to be extremely unhealthy but the situation is usually temporary, and refoliation occurs in most cases. Nevertheless, both height and radial increment can be severely checked. In India, for example, the teak defoliator *Hyblaea puera* (Hyblaeidae) (Fig. 6) causes reductions of 50 % in height increment, 66 % in basal area growth, and 61 % in volume increment (Nair et al. 1985). Long lists of defoliating insects are common in the literature, but without reliable impact data, management decisions are difficult to make. Some lepidopterous defoliators do not restrict themselves to leaf feeding; many also attack leading shoots and buds, especially when young. The yellow butterflies, *Eurema blanda* and *E. hecabe* are serious defoliators of various leguminous trees such as *Acacia* and *Paraserinathes* (Khan and Sahito 2012). They are ubiquitous in S and SE Asia, and have been reported to destroy all the terminal buds of its host tree,





**Fig. 6** Defoliation on *Tectona* by teak defoliator larvae, *Hyblea puera* (India) (Photo: Martin Speight)

as well as causing damage to 60 % or 80 % of the foliage (Roychoudhury et al. 1995). Conifers can also be heavily attacked by defoliating moth larvae, one of the best examples being the Masson pine caterpillar, *Dendrolimus punctatus* (Fig. 7) (He et al. 2006). This species is a widespread pest in many parts of southern China, where sophisticated control programs have been developed (see below).

Since the huge expansions of eucalypt plantations in Brazil, various defoliating Lepidoptera have become serious pests. Most of them are indigenous species that have swapped from native trees into the monoculture exotics (Kowalczyk et al. 2012). One extremely important example is *Thyrintina arnobia* (Zanuncio et al. 2000). Various natural enemies of this species have been identified, both parasitoids (Pereira et al. 2008), and predators (de Oliveira et al. 2011), but their effectiveness has yet to be demonstrated.

Another family of defoliating Lepidoptera in tropical forestry is the bagworms (Psychidae). Rather than living as caterpillars exposed on leaf surfaces, bagworms construct cases from dead leaf fragments within which they live, feed and eventually pupate. *Pteroma plagiophleps* (Fig. 8) is one species from S.E. Asia which has a broad host range from oil palm to mangroves (Remadevi et al. 1997), as well as various forest plantation trees. A final group of defoliating lepidoptera which are commonly found, especially in nursery situations, are the leaf rollers. Here, the larvae construct tents out of soft leaves rolled together with silk in which they feed and grow. *Strepsicrates rhothia* (Fig. 9) (Lepidoptera: Tortricidae) (Sidhu et al. 2008) is frequently found in eucalyptus nurseries in Vietnam and Thailand, for instance, but eventually damage appears to be slight. This is the key to defoliation; since most tree

**Fig. 7** Larva of pine caterpillar, *Dendrolimus punctatus* (Vietnam) (Photo: Martin Speight)



**Fig. 8** Bagworm larva, *Pteroma* sp. on *Paraserianthes* (Vietnam). Photo: Martin Speight



species have evolved alongside their defoliators, forest managers should not worry unduly about isolated albeit severe attacks. When defoliation is persistent and/or accompanied by attacks by secondary pests then it is time to worry.

- (b) **Shoot and cone borers.** Many species of Lepidoptera have larvae which for most of their lives live and feed inside the leading and lateral shoots of trees. Their impact takes the form of loss of height increment due to the destruction of dominant leaders, and severe deformation of trees because of lateral shoot compensatory growth. In extreme situations, trees resemble shrubs. One of the most widespread pests of mahogany are the moths *Hypsipyla robusta* and

**Fig. 9** *Eucalyptus* leaves rolled and tied by *Strepsicrates* larva (Philippines) (Photo: Martin Speight)



**Fig. 10** *Swietenia* attacked by mahogany shoot borer, *Hypsiypla* sp. (Costa Rica) (Photo: Martin Speight)



*H. grandella* (Pyralidae) (Figs. 10 and 11). The former species occurs all over S.E. Asia, Australia and Africa, whilst the latter is widespread in the New World (Floyd et al. 2003). Young larvae attack the leading shoots of young mahogany and other Meliaceae, causing extreme dieback and loss of increment.

**Fig. 11** Mahogany shoot borer larvae, *Hypsipyla* sp. (Australia)  
(Photo: Martin Speight)



In Indonesia, for example, 90 % of leading shoots were reported attacked and hence killed in three-year-old trees (Watt et al. 2003), whereas those beyond 13 or 14 years old were hardly attacked at all. Host tree resistance is extremely variable, linked to species, site and country of planting. Thus, for example, the Australian cedar, *Toona ciliata*, appears resistant to *Hypsipyla* when planted in Brazil (Carvalho Nassur et al. 2013).

Perhaps the most serious pests of tropical pines from central America to the Far East are the so-called shoot or tip moths. This large group of Lepidoptera belongs mainly to the families Tortricidae and Pyralidae, whose larvae tunnel into the leading and lateral shoots of all species of *Pinus*. The most common genera are *Rhyacionia* (= *Petrova*) and *Dioryctria* respectively (Figs. 12 and 13) (Bi et al. 2008). Infested shoots are killed, and trees become severely stunted (Speight and Speechly 1982). Growth is so retarded that projected timber returns at rotation may never be realized. Observations in the Philippines suggests that tree dominant height at a rotation age of 14 years reaches a mere 10 m, instead of the projected 18–25 m. Some shoot moth larvae also tunnel into the main stems of young trees, girdling them, or the cones of older ones, destroying seeds (Bhandari et al. 2006).

- (c) **Wood borers.** Larvae in the families Cossidae, and Hepialidae are commonly found as pests of tropical trees because of their boring into the main stems of trees. Normally, the trees are not killed, because the larvae live mainly in the heart wood, but severe if not complete degrading of the timber occurs. An example well known from the Far East is the teak beehole borer, *Xyleutes ceramica* (Cossidae) (Fig. 14) (Gotoh et al. 2007). The larvae tunnels up the center of tree trunks, leaving an access hole in the bark through which frass (feces) is ejected and from which sap exudes. This species is a serious pest of *Gmelina arborea*, and other Verbenaceae in Sabah and Peninsular Malaysia, where 50 % or more of mature trees in stands were attacked. Another cossid, *Zeuzera coffeae*, is a widespread pest of many tree species, such as *Cassia*,



**Fig. 12** *Pinus caribaea* stunted and branched by attacks from pine shoot moth, *Dioryctria* sp. (Vietnam) (Photo: Martin Speight)

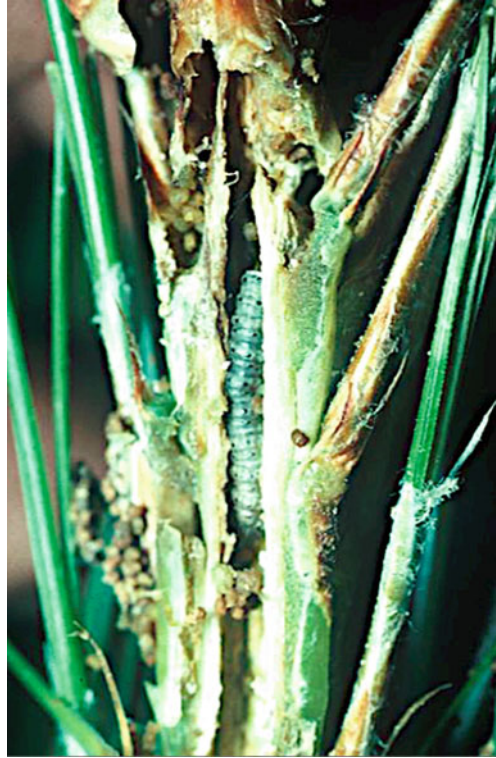
*Eucalyptus*, *Pterocarpus*, *Swietenia*, *Tectona* and *Toona* (Hutacharearn et al. 1988). The hepialid *Endoclitia signifera* has recently been reported to have shifted from native tree species into eucalypt plantations in southern China (Yang et al. 2013). Unlike most boring stem or bark insects, these pests do not seem particularly associated with host plant stress; more or less healthy trees can be attacked. Attack prevention is therefore difficult.

### **Hymenoptera: Ants, Sawflies, Wood wasps and Gall wasps**

The order Hymenoptera is sub-divided into three sub-orders, the Symphyta which contains the sawflies and wood wasps, the Parasitica, all specialized enemies of other arthropods, and the Apocrita, which contains the bees, ants and wasps. As far as tropical forestry is concerned, only the sawflies and the ants represent serious pests.

- (a) **Sawflies.** Larvae of the superfamily Tenthredinoidea closely resemble larvae of moths and butterflies in structure and function. They are all defoliators, and hence the earlier discussion on the impact of lepidopterous pests is equally valid for the sawflies. The genera *Gilpinia*, *Neodiprion* and *Diprion* are usually found on conifers of various species from Central America to S.E. Asia. As with many lepidopteran defoliators, these sawflies pose little long-term threat to plantations as long as their outbreaks decline naturally and do not persist for any length of time. This is especially to be expected in stands of tree species

**Fig. 13** Pine shoot moth, *Dioryctria* sp. larva (Vietnam) (Photo: Martin Speight)



indigenous to an area. In N. Vietnam, for instance, the sawfly *Shizocera* sp. periodically defoliated the native *Mangletia glauca* (Tin 1990) Complete defoliation sometimes occurred, but long-term losses were not thought to be significant; certainly, tree mortality did not seem to occur, and attacked trees rapidly refoliated.

- (b) **Wood wasps.** Wood wasps are another member of the Symphyta group within the insect order Hymenoptera; *Sirex noctilio* is a widespread albeit mainly temperate pest of various pine species. Their larvae are well known as borers within the timber of standing trees, causing not only physical damage but also introducing a symbiotic fungus which causes timber degrade.
- (c) **Gall formers.** Certain tiny wasps belonging to the Apocrita group of the Hymenoptera, are members of the superfamily Chalcidoidea, which contains many species of parasitoid that attack other insect species. However, a few species in the family Eulophidae are herbivorous. The burrowing activities of their larvae in plant tissues stimulate the production of galls, swellings and other growth distortions which reduce plant yield and produce deformities. *Leptocybe invasa* (Fig. 15) is now the most globally wide-spread pest in this group, despite only being recorded as an emerging problem in the early 2000s (Mendel et al. 2004). A typical invasive pest, *Leptocybe* now attacks species

**Fig. 14** Beehole borer, *Xyleutes ceramica*, larva in *Gmelina arborea* (Indonesia)  
(Photo: Martin Speight)



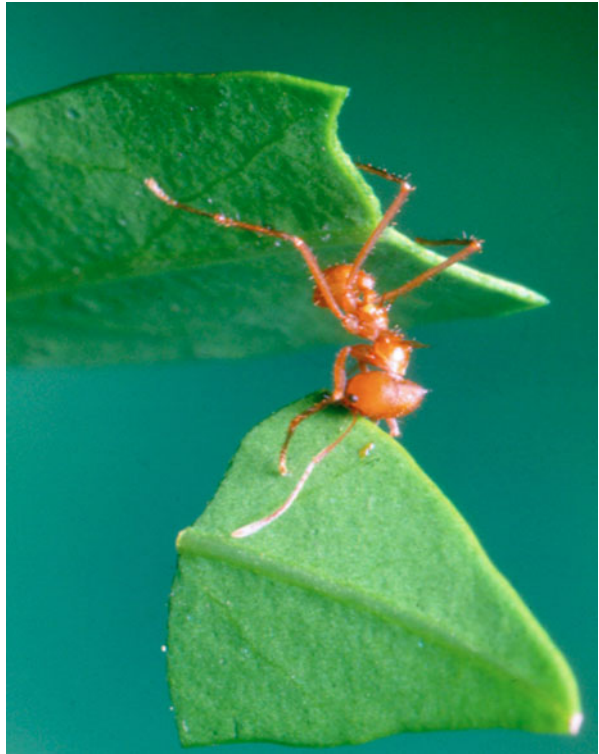
of *Eucalyptus* over many parts of the world, from its native home in Australia, to S.E. Asia, China, India, Africa, the Middle East and South America. The adult wasp is a mere 1 mm or so in length, and the female lays eggs in shallow leaf tissue of shoots and leaf petioles (Rocha et al. 2013). The hatching larvae cause the host plant to produce swellings – the galls – which deform the terminal leaves and shoots, leading to severe leaf fall and dieback; trees in the nursery and in young plantations are most affected (Zhu et al. 2009). *Eucalyptus* species show distinct variations in susceptibility to *Leptocybe* attack and subsequent damage (Dittrich-Schroeder et al. 2012), but such variation may be difficult to use as a prevention method commercially, since different genotypes of the same species may differ widely in their susceptibility to the pest. On top of this, there are problems with variations of site and climate at the local and regional level (Nyeko et al. 2009), as well as the likely problems of genetic variability within and between populations of the pest itself.

- (d) **Ants.** Most species of ant have no relevance to tropical forestry, but one New World group, the leaf cutters, can be extremely serious defoliators in Central and South America. Two major genera of leaf cutter ant are *Atta* and *Acromyrmex* (Fig. 16). Workers forage in the forest and remove leaf material

**Fig. 15** Galls on *Eucalyptus* leaves created by the blue gum psyllid, *Leptocybe invasa* (Turkey) (Photo: BJ Schoenmakers)



**Fig. 16** Leaf cutter ant, *Atta* sp. (Guatemala) (Photo: Paul Embden)



in great quantities to act as mulch for fungus gardens within the colony. In Brazil it has been found that leaf cutter nests in natural forest remnants can provide foraging (and ravaging) worker ants which defoliate trees in adjacent eucalypt plantations (Urbas et al. 2007).



**Fig. 17** Weevils, *Hypomeces squamosus*, defoliating *Acacia mangium* in nursery (Philippines) (Photo: Martin Speight)



### **Coleoptera: Beetles**

Of all insects (indeed, of all animals), beetles are the commonest in terms of numbers of species so far described. One family alone, the weevils, comprises around 80,000 species, whilst total numbers of species may reach 350,000. Many are herbivorous, feeding on a wide range of plant material. Because of their abundance, only certain families have been selected to illustrate the diversity of their activities and their importance in forestry.

- (a) **Curculionidae – weevils.** Characterized by extended head capsules, adult weevils feed as voraciously on plant material as their larvae. In most cases, however, the apodous (legless) larvae live in concealed habitats such as the soil, under bark, or inside seeds. Adults are predominantly external bark or leaf feeders, and as such can cause serious damage. One of the most conspicuous in S.E. Asia is the large iridescent green weevil, *Hypomeces squamosus* (Fig. 17), which can be a severe defoliator of eucalyptus and various leguminous and citrus crops (Chung et al. 2008). Another example of a polyphagous weevil is the genus *Myloccerus* (Sharma and Sood 2009) which has been recorded as a serious defoliator of dipterocarps and eucalypts. Some weevils, rather than feeding on leaves, attack the bark of young trees near ground level. These so-called root-collar weevils can kill young transplants by ring-barking them.

Other wood boring weevils such as *Aclees* spp. have begun to attack young *Cedrela odorata* in Vietnam (Thu et al. 2013).

One of the most widespread and troublesome weevils in mainly temperate or sub-tropical regions is the eucalyptus snout beetle, *Gonipterus scutellatus* (Mapondera et al. 2012). Originally a native of Australia, this beetle is now a pest in most eucalypt-growing regions of the world, from Argentina, Uruguay and Brazil to Lesotho, Malawi, Kenya and South Africa, a classic example of anthropocentric accidental spread of a pest. The larvae, and to a lesser extent the adults, feed voraciously on eucalypt leaves, resulting in the destruction of young twigs and shoots, and hence the severe stunting of trees.

- (b) **Chrysomelidae – Leaf beetles.** Adult and larval chrysomelids are defoliators with the same impact on host trees as lepidopteran or hymenopteran pests which feed on leaves. Though not extremely common, their local effects can be severe. The species *Calopepla leayana* occurs spasmodically in outbreak numbers in various parts of Asia, feeding on trees such as *Gmelina arborea* (Kumar et al. 2010).
- (c) **Scarabaeidae and melolonthidae – Cockchafers, Rhinoceros beetles, white grubs.** Scarabaeid beetles are pests in perennial tropical crops such as palms, but their impact is less significant in forestry. Adults may occasionally act as defoliators, but larvae often occur as root feeders in nurseries. These are the well-known white grubs which gnaw the bark and wood of most nursery species up to the root collar, causing widespread mortality. The larvae of species such as *Schizonycha ruficollis* (Kulkarni et al. 2007) and *Holotrichia rustica* (Kulkarni et al. 2009) can be extremely damaging in nursery beds of teak, *Tectona grandis* in India and neighboring countries. Adult beetles use natural vegetation around forest nurseries as refuges, and lay eggs in large numbers in the bare soil of the nurseries.
- (d) **Cerambycidae and Buprestidae – Longhorn Beetles; Round Head and Flat Head Borers.** Both families of beetle are notorious in the tropics as despoilers of timber and killers of younger trees by virtue of the tunneling activities of their larvae. Eggs are laid on the outside of host plant bark and the hatching larvae tunnel under the bark and feed at first between the bark and sapwood. In smaller trees, this can kill the host by girdling. Later, the larvae tunnel into the timber itself, creating large and extensive galleries packed with coarse wood fibers. As with many other forest pests, cerambycids and buprestids inhabit natural forest where they are usually destroyers of over-mature or moribund timber. Transferring to often nonvigorous or monoculture plantations, they can become a serious problem which is very hard to control. Usually, but not invariably, cerambycid and buprestid attack is indicative of host tree stress; vigorous trees are able to withstand the initial invasion of newly hatched larvae using sap pressure defence systems (Paine et al. 2011). Heavy infestations of *Shorea robusta* in the Terai region of Nepal by a buprestid only occurred in trees planted on waterlogged sites. The cerambycid *Hoplocerambyx spinicornis*, the so-called sal heartwood borer, has the distinction of being one of the earliest recorded major forest pests in the tropics, affecting thousands of hectares of *Shorea* forests in India in the 1920s

**Fig. 18** *Paraserianthes falcata* showing multiple galleries of the longhorn beetle, *Xystrocea festiva* (Indonesia) (Photo: Martin Speight)



(Sen-Sarma and Thakur 1986); it is still a serious threat today (Baul et al. 2013). In Sabah, *Xystrocea festiva* (Fig. 18) has been a serious problem in plantations of *Paraserianthes falcata* (Endang and Farikhah 2010), and, to a lesser extent, *Acacia mangium*. It seems particularly prevalent in forest stands near to secondary, natural forest, and death of trees is mainly caused by ring-barking. Other species of cerambycid also exhibit this habit of transferring from alternative tree hosts. *Oxymagis horni* is recorded as infesting up to 10 % of 9-year-old *Eucalyptus deglupta* in the Solomon Islands, but is known from at least nine wild tree species, and also as a pest of cocoa (Bigger 1988). Perhaps the best-known borer pest of eucalypt in Africa, South America, California, the Middle East and southern Europe is the cerambycid *Phoracantha semipunctata*. It normally attacks sickly or drought-stressed trees (Caldeira et al. 2002), but healthy young trees may be killed by the boring of the larvae under the bark and later in the wood. Most species of eucalypt seem to be susceptible (Hanks et al. 2001).

- (e) **Scolytidae and platypodidae – Bark beetles, pin hole and shot hole borers, ambrosia beetles.** These beetles are usually considered to be secondary pests of trees which normally only attack trees which are already stressed by climatic effects, primary effects of defoliation or disease, old age or felling. Unlike the

**Fig. 19** Larvae of the bark beetle *Dendroctonus valens* (China) (Courtesy by Nmsgsfz nd)



cerambycids, adult scolytids and platypodids enter the host plant themselves. Bark beetles lay eggs under the bark where the larvae produce typical engraving galleries, girdling the host when densities are high. Shot hole borers, or ambrosia beetles, carry on through the bark and into the wood itself, taking with them symbiotic fungi which stain the wood surrounding their tunnels blue or black. Wood degradation is thus the major impact. A great deal of detailed research has been carried out on the ecology and taxonomy of these beetles (Beaver and Liu 2013), and it seems that very few species preferentially select healthy living trees to attack, whether in plantations or natural forests. When attacks on healthy trees do occur, they are usually associated with exotic hosts which may not be well adapted to local conditions. Even then, large densities of attacking beetles are required to overcome the defences of the tree; in Malaysia, for example, field surveys have shown that most beetle attacks on *Acacia mangium* are abortive (they do not penetrate through the bark), until densities per 0.1 m<sup>2</sup> exceed 100 or so. One of the commonest genera in S.E. Asia is *Xyleborus*; over 150 species of this genus occur in Peninsular Malaysia, for example, and members have been recorded from over 50 host species in India (Chandra 1981). *Dendroctonus* is a global genus, some species of which are known to be serious bark-boring pests in the tropics. The red turpentine beetle, *D. valens*, (Fig. 19) is having huge impacts on pines in various provinces of China (Sun et al. 2013), whilst the southern pine beetle, *D. frontalis*, is a serious pest in native pine stands in Central America (Rivera Rojas et al. 2010). Perhaps the biggest hazard for standing plantations is an excess of moribund timber, either as a result of clear-felling or a natural disaster such as wind throw, in which bark and ambrosia beetles can build up enormous populations very quickly, resulting in mass attacks to otherwise resistant forests, which may succumb under the pressure of attack. To make matters even worse, it is very easy to transport such pests across the world in all sorts of timber imports such as logs and planks, introducing them into new areas where climatic and forest conditions are perfectly suitable for their establishment and spread.

## The Reasons for Insect Pest Outbreaks in Tropical Forestry

Table 1 summarizes some of the basic reasons for insect pest outbreaks. In essence, most of them relate to the provision of an abundant food supply for insect herbivores, and hence a high reproductive and dispersal potential. Insect herbivores can be considered to be opportunistic. Their food supply, plant material, is especially deficient in organic nitrogen, a basic necessity of animal life. Any increase in this type of food will promote insect abundance and hence pest damage. Additionally, because most insect herbivores are host plant specialists, and natural forest systems tend to be mixtures of suitable and unsuitable host species, any plantation system which increases the likelihood of an insect finding nutritious and specialized food increases the probability of epidemics. A further problem for insects is to find suitable breeding sites without which the food acquired as a growing larvae or nymph cannot be converted into offspring. One of the best ecological systems involving trees which provide many of the above requirements involves host stress. Stress is basically any reduction in vigour which a tree undergoes by virtue of its own environmental interactions (although felling is a very successful, man-made, stress-inducing system). Even subtle stress from which a tree may easily recover once conditions improve can provide the extra food and breeding sites needed to convert an endemic (low density) insect population to an epidemic (high density) one. Stress is accompanied by typical increases in the availability of plant organic nitrogen, and, on occasion, reductions in plant defences such as sap pressure and complexes of chemicals in leaves and bark. There is no doubt that the absolutely fundamental system for preventing insect pest outbreaks involves the practice of ensuring optimal vigour in forest trees.

### Climate Change

Certain situations are rather hard to avoid. Natural disasters such as forest fire, wind throw, drought or water-logging can provide increased food and breeding material in the forest for insects, and changes in climate, for example, a reduction in harsh winters, allow the overwintering of pests that would otherwise have died, can make

**Table 1** A summary of some of the main reasons for outbreaks of forest insects

<p><b>(A) Increased food supply for insects</b>                      Natural disasters                      Monocultures                      Neglected crop hygiene                      Susceptible host species</p>	<p><b>(C) Pest introductions</b>                      International trade                      Poor quarantine inspection                      National transport                      Deliberate introductions</p>
<p><b>(B) Unsuitable site conditions for crop</b>                      Soil deficiencies                      Climatic extremes                      Use of exotic species                      Host plant stress</p>	<p><b>(D) Absence of natural enemies</b>                      Exotic pest species                      Monocultures                      Side effects of pesticides</p>

matters worse (Carnegie et al. 2005). Some of these exacerbating factors can be avoided, or their impacts reduced at least, by avoiding planting tree species that are, for example, drought intolerant on aridity-prone sites, but in the longer term, the effects of climate change may be difficult to avoid.

It is very difficult, and indeed risky, to make general statements about how insect pests will react to climate change, since so many species have different responses to variations in temperature, humidity, rainfall, CO<sub>2</sub> levels etc. As Singh et al. (2010) point out “The impact of climate change on pests is likely to be highly variable, with some changes favoring the spread of certain pests whilst hindering others.” It is clear that the occurrence and magnitude of insect pests in all ecosystems can be strongly influenced by local weather conditions and more general climatic variations (Juroszek and von Tiedemann 2013), but is also the case that specific effects of climate change on tropical forest pests are almost entirely unknown. Predictions however can be made, which will need validating by research and firsthand experience in the relatively near future.

According to Roques (2010) climate change is likely to influence the survival, fecundity, dispersal and natural range of forest insects, and also aid the establishment of survival of exotic pests species introduced into new countries via increases in international commerce. Some amount of global warming is likely to enable some insect species to increase the number of generations per year (de Lucia et al. 2012), and changes in leaf chemistry under increased CO<sub>2</sub> levels might actually increase damage levels caused by herbivores, since foliage may provide fewer nutrients, necessitating the insects to eat more. It is also possible that climate change can influence food chains, such that natural enemy populations and dynamics are just as negatively or positively influenced by increases in temperature, changes or variations in rainfall patterns, as the pests themselves (van Bael et al. 2004).

Pangga et al. (2013) suggest that the effects of climate change on pest and pathogens operate at least in part through changes in plant structure and growth rate. Certainly, increased levels of CO<sub>2</sub>, raised temperatures, and/or too much or too little rain can alter nutrient and defence levels in host plants, with concomitant changes in pest survival and reproduction. Drought effects are particular well known, though changes in rainfall patterns which reduce precipitation might not always result in extra stress for trees, and hence heightened susceptibility to boring Lepidoptera, Hymenoptera and especially Coleoptera. Indeed, Jactel et al. (2012) published a meta-analysis (a specific literature review) of the effects of drought on damage caused by forest insects and pathogens, with varying results. For example, it was clear from their review of 40 or so publications that damage by secondary pests (such as wood or bark boring beetles) increased with the severity of tree stress caused by drought conditions, as did primary pests and pathogens. The conclusion of this analysis however was that in at least two-thirds of cases, drought was accompanied by increased tree pests, though that in itself suggests a general concept, i.e., drought stressed trees may well be more prone to insect attack. As should be expected, there are exceptions to this “rule.” There are other ways to stress a tree than depriving it of water; indeed, giving it too much water can also

cause stress. Ranger et al. (2013) studied the influence of flood-stress (waterlogging) in laboratory conditions, on the selection of host trees by ambrosia beetles such as *Xylosandrus germanicus*. They concluded that trees subject to waterlogged conditions attracted significantly more beetles, via changes in the hosts' olfactory chemistry.

Insect pests can be influenced directly by changes in climatic conditions. *Plecoptera reflexa* is a moth whose larvae can be serious defoliators of nursery stocks of *Dalbergia sissoo* in parts of India. Research by Garg et al. (2007) has shown that the incidence of the pest and numbers of larvae are positively correlated with increasing humidity, but negatively correlated with rising temperatures. In this example therefore, it is predicted that the pest will become more serious as the climate becomes drier and hotter. Note however that if temperatures get too high, even tropical insects may suffer and die (Kiritani 2013).

Another example of the influence of drier, warmer weather on tropical forests and the insects that attack them comes from Honduras. The southern pine beetle, *Dendroctonus frontalis*, is a serious bark borer of *Pinus oocarpa* and *P. caribaea* in Central America, and outbreaks of the beetle are thought to be linked to increases in ambient temperatures and decreased rainfall in the region (Rivera Rojas et al. 2010). Additionally, because of this combination of changing climatic conditions (drier and hotter), wildfires have become more frequent in the forests, which increases stand susceptibility to *D. frontalis* and many other potentially serious secondary beetle pests (Choi 2011), by significantly increasing woody breeding material and still-standing but stressed host trees (Singh et al. 2010).

Not all affects of climate change need be beneficial to pest insects. Cornelissen (2011) has discussed the predicted effects of elevated CO<sub>2</sub> levels, and concludes that increased CO<sub>2</sub> may influence host plant physiology such that the net result is leaves of relatively low nutritional quality for insect herbivores, with a consequent decrease in pest abundance.

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## Ecological Pest Management

### Monocultures

Once the species or provenance of a tree has been selected, the planting system is almost invariably some sort of monoculture. Natural monocultures do occur; natural forests, especially in temperate regions, tend to be dominated by single species, but the major differences between this situation and a plantation monoculture is that all the trees in the latter are of the same age and usually of very similar genetic constitution (exactly the same in the extreme case of clonal forestry). For insects searching for a specific type of host tree, typified by its age and genotype, monocultures provide an almost limitless supply of food which can easily be found without other, nonsuitable species, getting in the way and hiding the host. For many years, tree species and genotypes have been chosen based on silvicultural characteristics, such as growth form and yield (Ji et al. 2011) and only relatively recently

has pest or diseases resistance been considered. Indeed, the more distantly related tree species are in a mixed stand the less likely are problems with high levels of herbivory (Jactel and Brockerhoff 2007). It has been suggested that not only do nonhost tree species reduce insect pest problems by making it more difficult for the host-specific herbivore to find its desired host but that the other tree species in a mixture may in fact form a deterrent or natural barrier to pest expansion. So, for example, Alves Silva et al. (2013) suggest that mixing neem trees, *Azadirachta indica*, with mahogany, *Swietenia macrophylla*, reduces attacks on the mahogany by mahogany shoot borer, *Hypsipyla grandella*. In general, planting large areas of one susceptible genotype is fairly clearly asking for trouble. Some entomologists and silviculturalists contest the argument that planting forest monocultures increase the risk from insect pests (Vehvilainen et al. 2007). Plath et al. (2011) found little difference in tree growth and survival in the presence of herbivorous insects in mixed or single species trials with native tree species, whilst Arnold and Fonseca (2011) showed no differences in leaf damage in mixed natural forest and managed monocultures, both in Panama. In general terms though, there can be no doubt that growing extreme forest monocultures, especially plantations of exotic tree species, should be avoided where possible, on the grounds of higher pest susceptibility, especially where the forest stand is prone to stress.

## Site Choice

The suitability of a particular tree species or provenance to a particular site is of extreme importance when considering whether or not a tree is likely to become stressed. If, for example, a site is clearly dominated by native vegetation which consists of xerophytic species shrub, it must be clear that such a site would not be suitable for new forest plantations which demand (but will not receive) sufficient water (Ji et al. 2011). As stated elsewhere, stressed trees are usually more susceptible to pest attack, though this varies with the type of insect (borers and sap feeders being most likely to thrive on stressed trees – Koricheva et al. 1998) and it is therefore vital to match tree species or provenances to the soils, climate and ecological structure of the area to be planted. The associations between stress and insect attack are not always clear cut. In the Turkana district of N. W. Kenya, *Prosopis* spp. has been planted in desert conditions to provide much-needed fodder and fuelwood. Severe mortality of trees has occurred, and most dead or dying trees are infested with cerambycid beetles. It is likely that these trees would have died in the absence of pests, and the beetles are only present in the role of detritivores. Most stress situations are not so severe, and insects certainly do finish off trees which would otherwise have survived. Stress can also be produced by the action of insects themselves; defoliation is a case in point. Trees with their leaves temporarily removed are often attacked and eventually killed by borers such as bark and ambrosia beetles. Because these borers cannot usually attack trees successfully without the activities of defoliators, they are known as “secondary pests.” One such insect is the now almost global eucalyptus borer, *Phoracantha semipunctata*.



The larvae of this beetle tunnel between the bark and sapwood of trees, effectively ring-barking the host. The pest is undoubtedly much more serious when trees are planted in sites where water is in short supply (Caldeira et al. 2002), and on eucalypt species such as *E. grandis* that are drought-intolerant wherever they are grown. It would be thought that an obvious pest-prevention tactic for *Phoracantha* would be to not plant trees on arid soils, especially not *grandis*.

## Pest Reservoirs

Even if a tree is rendered susceptible to insect attack, the likelihood of damage depends on the availability of a reservoir of pests. Some insects are fairly polyphagous, so that most wild or secondary vegetation, or even established plantations, can act as pest reservoirs, but most are more specialized, and hence the likelihood of attack in a new plantation depends on the degree of relatedness between the new tree species and the already existing vegetation in the area. Thus, planting monocultures of exotic *Pinus caribaea* in areas in the vicinity of natural or older stands of native *Pinus kesiya* already infested with their specific herbivores such as shoot boring Lepidoptera is folly (Speight and Speechly 1982), especially if the new sites are likely to cause tree stress. Indigenous species are usually in coevolved balance with their insect herbivores, new forest plantations are not. A simple management strategy therefore is to use indigenous tree species; if this is not possible, exotics which are totally alien to their new site should be preferred. Another example involves leaf cutter ants in Brazil (Magistrali and dos Anjos 2011). Ant nests are common outside, but near to, *Eucalyptus* plantations, and the trees can suffer significant defoliation because of their proximity to native pest reservoirs. Occasionally however, establishing forest plantations close to natural vegetation may in fact reduce pest problems; in Brazil, native species of moth such as *Euselasia eucerus* appear to be less of a problem in eucalypt stands in the vicinity of natural habitats because native parasitoids and pathogens living in these areas are able to suppress insect pest in the plantations (Macedo-Reis et al. 2013).

## Exotic Pests and Invasions

The importation of insect pests into countries where they are not indigenous can be a source of tropical pest problems, but, for the most part could be substantially avoided using efficient plant health and quarantine legislation. International trade in living trees or their seed, and timber products, provides an efficient vehicle for the accidental introduction of insects and nematodes, but few countries in the tropics practice stringent import restrictions. Many widespread tropical forest pests have arrived in new countries via international trade or passive transport. Examples include the wood wasp *Sirex noctilio* (Slippers and Wingfield 2012), Leucaena psyllid, *Heteropsylla cubana* (Matimati et al. 2009), the bronze bug *Thaumastocoris peregrinus* (Nadel and Noack 2012), cypress aphid, *Cinara*

*cupressi* (Montalva et al. 2010), and the red gum lerp psyllid, *Glycaspis brimblecombei* (de Queiroz et al. 2013). In fact, the majority of serious insect pests in tropical forestry today have been introduced from other countries, in the wake of their host tree species being planted as exotics.

## Quarantine and Forest Health Surveillance

Though in many cases, it is too late to prevent these types of invasions (Ji et al. 2011), effective quarantine and forest health surveillance must be a standard part of any forest pest management program these days (Carnegie et al. 2005). Maintaining healthy forests is discussed later in this chapter. Imports of timber in the round or sawn, wood packaging products, processed materials etc. carry with them a great number and diversity of potentially serious forest pests (Humble 2010). Live plants are also another common route for invasive pests to enter a new country (Brockerhoff et al. 2010). Such pests must be intercepted at international ports if at all possible, assuming that their departure from source countries cannot be avoided, so routine and effective inspections systems must be put in place. Wylie et al. 2008 suggest a series of steps to be considered in forest pest quarantine measures, whether they be at international borders or indeed once the cargo has entered the new country. They are:

- Know what pests are already present
- Know what pests you don't want
- Assess the likely pathways for exotic pest entry • identify and categorize risk sites
- Have methods for detecting target pests
- Be able to identify what you find.

Inspections may involve physical techniques such as debarking immediately or waiting for potential emergences from products held in controlled facilities, or the use of pheromones to bait traps to detect the presence of novel pests. Clearly, if any of these techniques reveal pest species, immediate and effective sanitation procedures must be followed.

## Tree Susceptibility and Resistance

All sexually reproducing species vary genetically, and trees are no exception. Hence, there can be significant phenotypic variation within one trees species, as well as of course even more between species, within a genus or beyond. Some of this variation can be in terms of physical and chemical defences or deterrents to the feeding of herbivorous insects, which are characteristic of tree leaves, sap, bark and other plant parts. Thus, some genotypes of a particular tree species may be palatable, even attractive to herbivores, whilst others may be much less suitable.

These variations in host-tree palatability may be simply in terms of leaf toughness or nutrient content, or maybe much complex cocktails of poisons and toxins. Trees which insects find palatable and nutritious can be called susceptible, and the quest for the opposite, i.e., resistance, is an important tactic in modern pest management (Speight et al. 2008). Note that this type of resistance must be heritable, and not just a consequence of site or weather conditions;

A lot of forestry, whether temperate or tropical, is in the business of utilizing tree species and genotypes that have the most desirable silvicultural properties, such as growth rate, top height, timber yield, wood structure and so on (Evans and Turnbull 2004). Risk takers would maximize these sorts of parameters, and neglect those that mean the trees are less likely to be eaten or attacked. As Henery (2011) puts it, commercial forestry tends to place “selection for growth over defence.”

Physical defenses include simple leaf toughness, so that young caterpillar mouths are unable to chew on their food, or the provision of lots of leaf hairs (trichomes) which prevent both sap feeders and defoliators from gaining access to the leaves. An example of the latter is the tree genus *Corymbia* from Australia which is fed on by the leaf beetle *Paropsis atomaria* (Nahrung et al. 2009). *C. citriodora* has few if any trichomes on its leaves, and is frequently heavily defoliated by both larvae and adults of the beetle, whereas the closely related *C. torelliana* has very hairy leaves and in experiments at least, suffered 10 times less defoliation in average. Tree foliage can contain all sorts of oils, tannins, toxins and poisons, some at least having evolved specifically to combat insect feeding. Staying with *Corymbia* and *Eucalyptus* species, Steinbauer and Matsuki (2004) found a clearly linear negative relationship between the oil content of tree leaves and the final weight of autumn gum moth, *Mnesampela privata*, pupae. Small pupae mean smaller females with smaller numbers of eggs, resulting in many fewer pests in the next generation. So, tree breeders should be looking for genotypes that not only have desirable silvicultural characteristics, but also show various forms of resistance to insects (and diseases). However, time and again, this appears not to have been put into practice. For example, Gonçalves et al. (2013) reviewed the major species of *Eucalyptus* grown in Brazil. They looked at seven species and four hybrids, and concluded that all of these trees were susceptible or indeed very susceptible to a whole range of galling or sapfeeding insects such as bluegum chalcid, *Leptocybe invasa*, redgum lerp psyllid, *Glycaspis brimblecombe*, and bronze bug, *Thaumastocoris peregrinus* (all of which incidentally are as exotic to Brazil as the trees themselves). To make matters worse, many of these species or hybrids are produced clonally, and planted over large areas, thus producing extreme monocultures with high selection pressures for rapidly reproducing pests to overcome what little or transitory resistance there is. The future of resistance selection and breeding in tropical trees, though seemingly most sensible, is unclear. Other species of tree may show more scope for resistance traits in pest management. Progenies of *Dalbergia sisso* were found to vary significantly in their resistance to the potentially lethal wood boring beetle, *Aristobia horridula* in Nepal (Dhakal et al. 2005). Similarly, *Gmelina arborea* is now a widely planted broad-leaved tree native to parts of Asia and South east Asia, and field trials in India have shown that

over 30 % of clones of this one trees species show high or moderate resistance to defoliation by the beetle *Craspedonta leayana* (Kumar et al. 2006). Couple this with a reported 80+% mortality of *C. leayana* pupae by the parasitoid wasp *Brachymeria excarinata* (Singh et al. 2006), and a potentially successful IPM program can be envisaged (see below). However, it has yet to be seen whether or not such examples of resistance are heritable, survive genetic interbreeding, and work over a wide range of sites and environmental conditions. Henery (2011) in fact is of the opinion that selecting for resistant genotypes for insect pest management in trees is unlikely to be successful.

## Stand Management

Silvicultural practices should be directed towards promoting and maintaining forest health (Bi et al. 2008), and healthy forests tend to be less prone to pest problems. Once trees are planted, some amount of manipulation may be possible to reduce pest attack and damage. Little ecological manipulation is possible at the nursery stage, since young trees are grown in an intensive, almost horticultural manner which makes them prone to insect attack. They are usually highly palatable with low pest resistance, and are grown in intense monocultures with high inputs of fertilizers and pesticides. It is important to ensure that the transplants are as vigorous as possible when placed in a new stand; sickly transplants are unable to withstand the shock of planting, and may soon succumb to insects and other depredations. The production of healthy transplants is essential. It is simple to induce stress in a young tree if it is mishandled in the nursery; root coiling caused by clumsy pricking out or potting on can result in termite attack on the roots in later life or a general reduction in plantation vigour. Plant spacing can have an influence on the future pest problems; it is suggested that close spacing of *Swietenia* encourages the height growth of trees and hence reduces the length of the critical period during which the trees are susceptible to the shoot borer *Hypsipyla robusta*. However, shady conditions can reduce the same tree's growth rate, whilst limiting attacks by these borers (Opuni-Frimpong et al. 2008a), a trade-off that may have some merit in an IPM program (see below).

Competition amongst a stand of rapidly growing trees is another way of reducing their vigour, and hence increasing their susceptibility to insects. Proper thinning to an optimal spacing before competition becomes too intense can reduce pest attack considerably. Thinnings must not be left lying in the stand; forest hygiene methods such as removal and destruction or *conversion* of brashed, pruned or thinned material is essential to prevent the build-up of pests which could attack the standing trees. The same is true at the final felling stage; logs with bark on should not normally be allowed to lie in the forest for any length of time (3 or 4 weeks would be maximum in humid tropical climates) before conversion. On occasion, it may be useful to leave moribund timber lying around. If a stand becomes infested with wood borers, it has proved possible to utilize a trap tree system to attract adult insects away from standing but susceptible trees by felling suppressed or infested

trees and leaving them in piles to which pests are preferentially attracted. The logs are later destroyed and with them the pests. This ecological system has worked in the past in India for the control of the sal heartwood borer, *Hoplocerambyx spinicornis* (Nair 2007).

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## Chemical Control

Chemicals available for the management of pests in tropical forestry can be split into two broad groups, the pesticides (insecticides, nematicides etc.) which are basically poisons or hormone mimics, and behavior-modifying chemicals such as sex-attractant pheromones.

### Insecticides

All manner of poisons and toxins have been used to kill insect pests for many decades (Devine and Furlong 2007), although the overwhelming majority of these have been used in agriculture or public health. Forestry, especially tropical forestry, has seen very little use of these chemicals, and is likely to see even less in the future.

Apart from in nurseries, pesticides in tropical forestry can in the main be discounted as too expensive for economic viability. It must be remembered that the major part of the cost of chemical control is the application system required; in the case of any plantation forest beyond the establishment phase, this almost invariably means an air-borne delivery system such as a fixed-wing aeroplane or, even more expensive, a helicopter. Just occasionally it is possible to use ground-based delivery systems for mature plantations; thermal foggers which produce an insecticide-rich smoke cloud have been used to control leaf cutter ants in Brazil and other parts of South America (Cameron 1989), but since this system is often difficult to restrict in its coverage, there is a substantial risk of environmental pollution. Often the technology is unavailable anyway, and poor or inefficient applications are worse than doing nothing. In general terms, a very high percentage kill is required to quell a pest population and prevent its resurgence. Eighty percent mortality, for instance, will leave 20 % alive, of whom many will be selected for pesticide resistance. The natural regulatory factor of intraspecific competition for food and space will be reduced considerably, and with even a low fecundity (in this case 10 eggs per surviving female, assuming a 1:1 male: female ratio) will bring the pest population back to where it was prior to treatment. To make matters worse, natural enemies which may on occasion be economically beneficial (see below) may be easily destroyed. Even in situations where money and technology are both available, it may be impossible to achieve these high mortalities required. Many insect and nematode groups are protected from pesticides by virtue of their mode of life; thus leaf miners, gall formers, root feeders, shoot, bark, wood and cone borers, are all very difficult to get at with poisons, especially since the more effective

systemic insecticides are usually the most expensive. Then there is the problem of resistance. Even some of the newest insecticides available are now showing signs of being less effective because insects pest are evolving resistance to them. Imidacloprid, for example, is one of the newest types of insecticide available. However, though not used much at all in forestry, it's widespread use against defoliators, borers and sap feeders in agriculture and horticulture the world over has rather rapidly seen the appearance of resistance in various pest insects (Tiwari et al. 2011). All in all, it is unlikely that tropical foresters would ever consider pesticidal use except in the special cases of nurseries or at the planting stage.

As has been said before, forest nurseries approximate to a horticultural crop. They are small scale, easily monitored to assess pest incidence and impact, and readily accessible for treatment. The value of seedlings is relatively high, and hence some pest control is therefore viable. Even then, gross errors can be made in the use and hence efficacy of pesticides. A great deal of time and money is squandered in inefficient, poorly timed and wasteful insecticide use, with phytotoxicity commonplace. The choice of compound may well be very limited, but it is important to realize that old-style, broad spectrum insecticides are (a) inefficient because they do not reach their target and (b) dangerous because of their broad range and persistent properties. Most insect pest control in nurseries can be carried out only when inspection reveals high numbers of pests or large amounts of damage.

Apart from the nursery, insecticides are only occasionally economically sensible in a case such as severe damage by termites to young planted trees. Although many trees are fairly resistant to termites even at the delicate establishment stage, the choice by silviculturalists often includes very susceptible species, such as pines and eucalypts. Historically, long-persistent organo-chlorine insecticides such as aldrin and heptachlor have been used in the planting holes of each tree, with considerable success in many tropical countries. With increased concern about public safety and environmental hazards associated with these compounds, legislation by many countries or via aid agencies has precluded their use, despite their obvious efficiency. Persistence of toxicity is required for up to a year after planting, and some useful chemicals have been developed with slow release formulations, but these have proved to be prohibitively expensive (Logan et al. 1992). Less environmentally harmful compounds such tropical plant abstracts (Osipitan and Oseyemi 2012) or neem oil (El Atta et al. 2011) are unlikely to work terribly well if at all.

## **Pheromones**

Many volatile compounds known as pheromones have been identified and isolated from insect pests in forests, especially Lepidoptera and Coleoptera. The former order of insects mainly uses pheromones to attract mates, whereby adult females release pheromones which males use to locate them. The latter order may also use sex-attractant pheromones, but they also use them to form aggregations of the adult beetles to overcome host-tree defences (Wyatt 2014). Synthetic versions of some of these compounds are now available which mimic an insect's own chemical

communication systems. Such compounds are now routinely used in many agricultural and horticultural systems to monitor pest levels, provide decision-making data for spray programs, and to reduce mating between male and female adult pests so that significantly fewer eggs are laid (Nadel et al. 2012). So far however, little or no commercial use has been made of this in tropical forestry, although some major tropical forest pests have been studied. In China, for example, the complex chemistry of sex-attractant pheromones of the yunnan pine caterpillar moth, *Dendrolimus houi*, and the goat moth *Zeuzera leuconotum*, and have been elucidated (Kong et al. 2007; Liu et al. 2013), but as yet there are no suggestions as to how to deploy these compounds in forest pest management strategies. However, some progress has been made with pheromones of the Chinese pine caterpillar, *Dendrolimus tabulaeformis* (Kong et al. 2012), and the masson pine moth, *D. punctatus* (Zhang et al. 2003) for use as monitoring tools for pests incidence and abundance. Assuming a one-to-one male/female ratio, it is possible to assess forthcoming pest (defoliating larvae in these cases) densities by counting male moths attracted to pheromone baited traps, relating these to female numbers, and, knowing average fecundity values, estimating the numbers of eggs laid, where and when. Such tactic work very well in certain agricultural and horticultural situations where monitoring can lead to effective management techniques, but in tropical forest stands, even if pheromone monitoring works, subsequent control may not be available.

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## Biological Control

### Predators and Parasitoids

There is a great deal of dogma both in the literature and in the minds of biologists and silviculturalists about the merit of biological control, and the use of natural enemies in pest control. The basic debate revolves around the understanding of what factors are most important in either maintaining pest populations at low levels, or reducing them when they have become high. As has been discussed earlier, opportunist herbivores such as forest insects tend to be limited predominantly by their food supplies, and since forestry does have a tendency to increase this food supply, then natural population regulation fails. In many cases, parasites and predators of pests cannot keep up with growth and dispersal rates of pest insects when their food is super-abundant and they are at epidemic levels. In most cases therefore, insect epidemics have to be reduced by other means before biological control using parasitic or predatory insects can be expected to be at all efficient in the short term. To make matters worse, the likelihood of natural biological control occurring decreases as the host plant and/or pest becomes more exotic and the planting conditions less natural. Perhaps the major advantage of forest stands in terms of the potential for successful biological control (when compared with agricultural landscapes) is that forests are long-lived, relative undisturbed

ecosystems (Day et al. 2003), wherein some degree of stability between pest and enemy might be expected to develop (at least until felling).

Nonetheless, many workers advocate the use of biological control using predators, or especially parasitoids, to control (or more accurately in ecological terms, regulate) insect pests in forests. Wingfield et al. (2013) for instance state that “biological control represents the most important approach to reduce damage to nonnative insect pests of eucalypts.” However, Garnas et al. (2012) are of the opinion that “current efforts and scope for developing such (biological) controls are woefully inadequate for dealing with the increasing rates of pest spread.”

One of the most important features that “makes or breaks” a biological control program is the relative growth rate of the pest and its enemy. If the pest can reproduce fast and disperse efficiently, it may be unlikely that the enemy can keep pace, and though there may appear to be a relationship between pest and enemy numbers, it is the pest that is regulating the enemy in a bottom up fashion, not the other way round (top-down) which biological control requires.

In some situations, native insects become pests if exotic tree species, whereupon native natural enemies start to take a toll of these increased pest populations. In Brazil, for example, the larvae of various indigenous lepidopteran species have been found to damage eucalypt plantations, and a native predator of these pests has been identified which appears to rapidly follow defoliator outbreaks (de Menezes et al. 2013). *Brontocoris tabidus* is an heteropteran predator that feeds on many species of moth larva, but its ability to significantly reduce pest populations in *Eucalyptus* stands has yet to be evaluated.

These days, it is frequently the case that the new exotic insect pest spreads through a new region or country in the absence of natural enemies that may be abundant in the pest’s native home, but have to be discovered, reared and released in the new forests (Yang et al. 2014). Rarely do natural enemies seem to be capable of causing high mortalities, though, for example, Kurylo et al. (2010) report up to 100 % parasitism of a psyllid species feeding on eucalypts in Brazil. The bronze bug, *Thaumastocoris peregrinus* is an Australian native which has spread to many countries in Africa and South America. Nadel and Noack (2012) feel that the only feasible option for managing the bug in these new countries is biological control utilizing the parasitic wasp, *Cleruchoides noackae*, also from Australia. The snag is that the development of an efficient rearing and release system of the enemy has yet to be commercialized, remembering that it is one thing to achieve some establishment of the enemy species in the recently invaded country, but quite another to reduce the numbers and impacts of the pest to an economically acceptable level. Another sapfeeder, the cypress aphid, *Cinara cupressi* (later to be named *C. cupressivora* in Africa) has been a serious pest of tree species within the Cupressaceae for many years in parts of East Africa and more recently Chile (Montalva et al. 2010). Huge efforts were made in the 1990s especially to set up a classical biological control program for the aphid using a parasitic wasp, *Pauesia juniperorum* (Kairo and Murphy 2005), but to this day, *Cinara* is still a problem around the world, and the success of the biological control program is hard to evaluate, but at best is probably only partial (Day et al. 2003).



## Pathogens

It remains likely that the only biological control agents which may have the ability to rapidly control forest pests at high or outbreak densities are the pathogens. Fungi, bacteria and viruses all have considerable potential to control forest pests in various parts of the tropics, and several tropical countries such as India (Kumar et al. 2008), China and Brazil (Li et al. 2010), are pushing hard to replace the use of chemical pesticides wherever possible with entomopathogens, otherwise known as biopesticides. A word of caution is required at the outset; laboratory trials which show efficacy do not necessarily mean that commercial field operations will be successful since delivery systems still rely to a great extent on aerial application. Additionally, pests which in the lab can easily be exposed to pathogens may, as in the case of shoot borers, for example, be concealed from the infection.

### (a) Fungi

Pathogenic fungi which kill insects occur naturally in temperate and tropical forests (Jia and Liu 2010), and genera include *Entomophaga*, *Nomurae*, *Paecilomyces*, *Metarhizium* and *Beauveria*. *Metarhizium anisopliae* is mainly used against agricultural pests, but *Beauveria bassiana* has been trialed against a variety of forest pests in various countries. A big advantage of fungi as insect pathogens is that they are usually able to enter the body of the insects via spiracles and between body segments, whereas bacteria and viruses have to be ingested (eaten) by the host. One snag is that they are only really efficient in moist, humid conditions, but this is rarely a problem in tropical forests. *B. bassiana* has proved effective at killing termites in India (Nagaraju et al. 2013) and bark beetles in China (Zhang et al. 2011b). In fact in the latter case of *Dendroctonus valens* a serious pest of pines, a total of 88 different strains of *Beauveria* were isolated from soil, bark, frass, and living and dead beetles (Tao et al. 2012). Converting this impressive natural abundance into commercial and large scale control tactics has however yet to be achieved in most tropical forests, though some success is reported in China using inundative releases of the fungus to control pine defoliating caterpillar, *Dendrolimus punctatus*, a culmination of several decades of research and development (Li 2007).

### (b) Viruses

The viruses seemed to hold much promise some years ago, but have not in many cases realized predicted potentials. Many types of viruses infect insects, most of which have some similarity to vertebrate (including human) or plant viruses, hence rendering them inappropriate for use in pest management. However, one group, the baculoviruses, are entirely specific to arthropods, in most cases in fact to single species, and hence could be used without fear of harming the environment. Most common and, in most cases, effective amongst forest insects is the baculovirus group of Nuclear Polyhedrosis Viruses or nucleopolyhedroviruses (NPV's). NPVs have been used on a limited basis against various forest insect pests in the USA and Europe, but few if any are

currently commercially available. They crop up fairly regularly as natural epizootics. In 2009 for instance Castro et al. identified a new NPV from lepidoptera larvae feeding on trees in Brazil, but although its molecular and cellular characteristics were investigated, there has been no further development to date as a pesticide. Where they have been used semicommercially, NPVs can be very successful. An early example concerns *Lymantria ninayi* (Lepidoptera: Lymantriidae) is one of the most important defoliators of *Pinus patula* in Papua New Guinea. Naturally occurring NPVs have been associated with the collapse of pest populations, and trials have been conducted into the use of this NPV as a management tactic (Entwistle 1983). This particular virus remains active for up to 6 years in the soil or bark crevices and relies on rain to transfer it from these sites to places on the host plant where eggs or first instar *L. ninayi* larvae will encounter it. More recently, a lot of research and development has been carried out on the control of teak defoliator moth, *Hyblaea puera* in India. Natural populations of *H. puera* have been found to be infected with *Hyblaea puera* nucleopolyhedrovirus (*Hp* NPV) at rates varying from 50 % to nearly 90 % of the populations of later stage larvae (Bindu et al. 2011). Viruses can be collected in the field for application to new outbreak areas (Sudheendrakumar et al. 2004) either from the air or from ground based devices. However, the development of mass multiplication of *Hp* NPV has led to in vivo production which produces yields up to a 33,000 fold increase over the original inoculation concentration (Sudheendrakumar et al. 2008). So successful has this biopesticide become that it was patented by the Kerala Forest Research Institute in India, and given the trade name “Hybcheck” (Sajeev et al. 2007). One new problem has unfortunately been detected; high density populations of *Hyblaea* larvae (the very ones where control is needed most) do seem to show some resistance to *Hp* NPV (Bindu et al. 2012).

(c) **Bacteria**

Of all the pathogens, there is no doubt that the use bacteria as biopesticides is most widespread globally, particularly in agricultural crops. *Bacillus thuringiensis* is an insect-specific bacterium made up of many different strains or varieties with different properties and target organisms. For example, *Bt* var *kurstaki* is specific to lepidopteran larvae, whereas *Bt* var *isrealensis* targets dipteran larvae. All work in much the same way; living bacteria replicating inside a host gut (hence the need for ingestion) produce a delta-endotoxin crystal as a by-product of metabolism, which essentially kills the insect by creating holes in the midgut. In fact, commercial formulations of *Bt* do not contain living bacteria at all, merely the toxic crystal which is presented in different types of genetic varieties classified as “Cry” genes, e.g., Cry I, Cry II, and so on. Though *Bt* is in widespread use in agricultural crops all over the world, and on some forests in the USA, for example, it has so far seen very little application in tropical forestry. If delivery systems can be developed that are efficient and cheap, then controlling defoliator outbreaks may be a possibility, but note that no current strains of *Bt* will work on sap feeders or gall formers. One limited example involves the larvae of the moth *Pyomaxia* sp., a defoliator

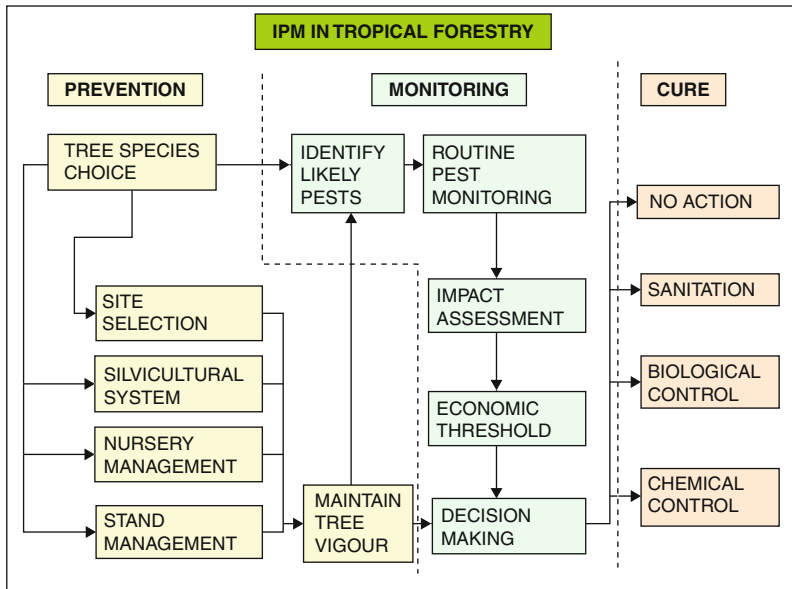
of mangrove forests in China. Li et al. (2007) were able to achieve over 90 % mortality. In India, the teak skeletoniser moth, *Eutectona machaeralis* was controlled by spraying formulations of *Bt kurstaki* from the ground into teak canopies, producing over 77 % mortality after three days (Meshram et al. 1997). There are two big drawbacks. Firstly, Bt does not persist as an active pesticide in the forest environment for very long, unlike most fungi and viruses (as well as certain chemical insecticides). Secondly, widespread resistance to Bt has been detected in pest insects across the world (Gassmann et al. 2009), so its future looks somewhat limited. A final use of Bt toxins is in transgenic plants, whereby crops such as maize and cotton are genetically modified to produce Bt toxins when fed upon by insect pests (mainly Lepidoptera). Many thousands of hectares of crops are GM modified in this way, and some tree species such as transgenic poplar have been tested with some success in the temperate regions of China (Zhang et al. 2011a). In tropical forestry however, there are no examples of GM trees being available and it seems unlikely that such a pest management system will ever be commercially viable, even if desirable.

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## Integrated Pest Management

This account has been subdivided into separate sections for ease of study of various management tactics. In reality, however, all appropriate preventative and curative systems should be used as a package throughout the life of a forest crop to maintain insect numbers and their impact below economically serious levels. This is termed integrated pest management (IPM). Figure 20 lays out a basic framework in the form of a flow chart. In its simplest form, it can be considered as a simple decision making system at the planning stage, where concepts plant vigor and resistance are coupled with site details to produce a healthy, nonsusceptible crop (Liang and Zhang 2005). All single techniques from ecological control to chemical control and biological control form part of an “IPM toolbox” (Speight et al. 2008) from which pest managers and foresters can select appropriate tactics.

Even before the “toolbox” is employed, there are some fundamental requirements which underpin any IPM strategies. Nyeko et al. (2007) present four categories of such requirements, i.e., Institutional strengthening, political support, research, and information exchange. Institutional strengthening (in developing countries in particular) involves regional training, international collaboration and the provision of sustainable forest practices that maintain the health of plantations. Political support asks that plant protection measures and tactics are properly funded and conform to international agreements on plant health, quarantine and so on. Research has to provide information on pest ecologies, population dynamics, host-plant relationships and susceptibilities (Wylie et al. 2002), whilst finally, information exchange enables all of this basic information and best-practice strategies to be readily shared between countries and regions, coupled with a proliferation of extension services, so sound advice is made available to the forestry



**Fig. 20** Flowchart depicting stages in IPM in tropical forests (From Wylie and Speight 2012)

industries themselves. As Garnas et al. (2012) point out, many tropical forest pest problems are now global, and their solutions need to be addressed at the same scale.

## IPM Examples

Case studies are the best way of illustrating the practice of IPM. It must be emphasized that these case studies describe potential management systems; so far their commercial use has been minimal. Many of these examples emphasize several basic problems with the commercial implementation of IPM programs. Most are complex and elaborate, requiring detailed knowledge of the pest and host ecology and biology. A great deal of planning is required, and many procedures are labor intensive. There are no easy “recipes” for successful IPM (with the exception of ensuring host vigour and reduced pest reservoirs); each package has to be designed from scratch to fit special characteristics. Most importantly, the basic knowledge is often lacking. Whether tropical countries or individual projects within them have the resources and expertise, or even desire, to establish IPM programs in their forests in the light of these problems is open to debate.

All successful IPM programs require prior knowledge of a pests’ status and likely impact. Without such information, any control or management decisions cannot be based on sound economic grounds. Note above all that the key to IPM in tropical forestry is prevention – if things do not go wrong in the first place or if they do the actually damage is below an economic threshold, then control will be unnecessary.

Two detailed examples will illustrate the ways in which various appropriate pest management techniques may be combined to go some way at least towards practical IPM systems. One example concerns a long-standing and seemingly intractable pest, the mahogany shoot borer, *Hypsipyla* spp., and the other a newly emerging tropical forest pest, *Leptocybe*.

(a) **Mahogany shoot borers, *Hypsipyla* species**

Over the years, many reviews have updated the then current state of knowledge and practice for the management of mahogany shoot bores in the genus *Hypsipyla* (e.g., Newton et al. 1993; Speight and Wylie 2001; Floyd et al. 2003; Wylie and Speight 2012). One most crucial point is that the taxonomy of mahogany shoot borers is still to this day complex and unclear. Horak, as far back as 2001, used molecular techniques to show that at least eleven species of *Hypsipyla* could be identified across the tropical world, but even 2014, papers are still being published naming just one species from each of the New and Old Worlds. Any management systems against a pest whose very taxonomy is unclear might not be as successful as one would hope.

The reviews propose various different techniques for the management of *Hypsipyla* species, which can be summarized as (a) Host resistance, (b) Tree/stand manipulations, (c) Chemical control, and (d) Biological control. In other words, all components of an IPM program have been studied and trialed at one time or another, with varying, but mainly little, success. The following sections bring the knowledge base up to date.

(a) Host resistance

Rapid tree growth is thought to be a key to avoiding the worst effects of shoot borer attack in various species of mahogany (Ward et al. 2008), and hence selection for this characteristic (subject to site influences) is an important goal of provenance trials. Other important factors to select for when looking for pest resistance are strong apical dominance and vigorous height growth (Cunningham and Floyd 2006), and tolerance of trees when attacked is also an important trait (Cornelius 2009). However, there is no point in finding differential host tree resistance to pests such as *Hypsipyla* larvae if the traits observed in the forest have little or no heritability (Wightman et al. 2008). These authors suggest that selection trials for pest resistance need to be carried out separately on high quality and poorer sites, and the best performing trees selected from both situations for future plantings.

Most work on host tree resistance to *Hypsipyla* boring has been carried out on young trees, from planting to 3 or 4 years old, since that is when most of the damage is done. However, Opuni-Frimpong et al. (2008b) suggest that in the case of African mahoganies at least, it is more reliable to wait until the trees are more mature. One reason for this is that young trees which are attacked in fact manage to grow out of the problem and are capable of producing a reasonably straight and unforked trunk as the years go by.

(b) Tree manipulations

Planting mahoganies in countries or regions where *Hypsipyla* doesn't occur would seem to be an obvious solution to the problem. For example, it seems that Dominica is free of borers, and the mahogany *Swietenia macrophylla* does much better there than in its native range of central America (Norghauer et al. 2011). Other remote islands such as Fiji appear borer free, but these are literally and metaphorically isolated examples, since the pest genus is hugely widespread across the tropics.

Most species of trees grown on plantations in the tropics are exotic to the country in which they are newly planted, and it is relatively rare to establish native species because of potentially enhanced risks from indigenous pests or pathogens (Plath et al. 2011). In the many reported cases of *Hypsipyla* attacks to native and exotic species of mahogany, there is no clear lesson to be learned, though it is suggested that exotic species may be attacked less in certain situations since the local, indigenous *Hypsipyla* species or genotypes may find the exotics less suitable as hosts, at least in the early days. An example of this is the Australian native, *Toona ciliata* that grows well in Brazil and seems not to be attacked significantly by the borer (Carvalho Nassur et al. 2013).

As discussed earlier in this chapter, planting trees in species mixtures rather than monocultures can on occasion reduce pest problems. For mahogany silviculture, this can mean mixing with other plantation species not in the family Meliaceae. For example, Alves Silva et al. (2013) tried interplanting neem, *Azadirachta indica*, with the mahogany *Swietenia macrophylla* in Brazil, in the hope that the neem would act as a natural barrier to the pest. Borer attacks were not prevented. Alternatively, enrichment plantings can be carried out, where mahogany trees of various species are established in gaps created by selective logging in natural or seminatural forests (Lopes et al. 2008). In Brazil, for example, Grogan et al. (2005) found that attacks by the borer were low when the mahogany trees were surrounded by dense secondary vegetation. Additionally, Goulet et al. (2005) discovered in Honduras that borer attacks on young trees were least when weedy strips were allowed to proliferate between the rows of trees, whilst mixed planting with maize (taungya) actually made pest problems worse.

Unfortunately, the competition for nutrients, light and water that the young mahoganies are exposed to from native vegetation may preclude these techniques for having commercial viability. Opuni-Frimpong et al. (2008b) tried planting various African mahoganies in various shade levels, and found that indeed *Hypsipyla* attacks became much less as shade increased. Sadly, the growth of the mahoganies in deep shade was also very low.

On a small scale, where individual trees can be dealt with, pruning and grafting has been shown to influence the effects of borer attack. If resistance traits can be discovered, it may be possible to use resistant root stock on

which to graft susceptible but otherwise desirable scions. In experiments Perez et al. (2010) found that the resistance from the rootstocks was passed to the otherwise susceptible grafts, but whether this is a long term, large scale, practical system has not been established. Pruning of trees forked because of borer attack to produce just one leader may have some merit (Martinez-Vento et al. 2010).

(c) Chemical control

It is difficult to consider practical methods of killing mahogany shoot borer larvae with contact insecticides because of the fact that they spend most of their lives concealed in their tunnels within shoots. Systemic chemicals, which are translocated by the tree, would be unlikely to be efficient enough to reach the larvae, especially as the trees grow taller. It is true that lab experiments readily demonstrate that synthetic insecticides such as carbofuran can kill *Hypsipyla* larvae (Soto et al. 2007), and that small-scale field trials also demonstrate the high efficacy of deltamethrin applied weekly on 2-year old trees in preventing borer attacks (Goulet et al. 2005), but even if such techniques were economically viable, their practical application at plantation scale seems very limited.

Instead, any chemical usage against mahogany shoot borer is likely to take the form of deterrents, or behavior modifying chemicals such as pheromones. Soto et al. (2011) tried using methanol and diethylether, to extract phagodeterrent chemicals from bitterwood, *Quassia amara*, to deter the feeding and tunneling of *Hypsipyla* larvae, with little success. Crude extracts of rue, *Ruta chalepensis*, were found to have some deterrent effect to third instar *Hypsipyla* larvae (Barboza et al. 2010). Abraham et al. (2014) were able to demonstrate responses by adult *Hypsipyla* to extracts of volatile chemicals from African mahoganies, but it is difficult to imagine the use of these extracts in commercial quantities, especially in the wet tropics.

Sex-attractant pheromones of *Hypsipyla* species have rather surprisingly received little research attention. Apparently, synthetic compounds do exist that mimic *Hypsipyla* sex-pheromones but apart from one or two hard to substantiate field trials back at the turn of the twenty-first century, nothing is available at the current time.

(d) Biological control

Papers are published fairly regularly that describe predators or parasitoids that have been found attacking *Hypsipyla* larvae or pupae. Predators include weaver ants (Peng et al. 2011), and parasitoids include various species of hymenopteran in the families Braconidae (Pinto et al. 2014), Eulophidae (Zache et al. 2013), and Ichneumonidae (Yoshida et al. 2010). Pathogens such as the fungus *Metarhizium anisopliae* are known to infect and kill *Hypsipyla* larvae (Balachander et al. 2012), but in practice, none of these biological control agents are likely to have sufficient efficacy to stop borer attacks on trees in susceptible plantations.

So where does that leave us? Nothing has really changed since the international workshop on mahogany shoot borer ecology and control

held in Sri Lanka in 1996 (Floyd and Hauxwell 2001), and growing tropical mahoganies of many species in plantations still has major pest management problems. This has to be one key example of IPM in tropical forestry which may never have a viable solution.

(b) **Eucalyptus gall wasp, *Leptocybe invasa***

Unlike *Hypsipyla* species which have been familiar pests for many decades, the eucalyptus gall wasp, *Leptocybe invasa*, is a newcomer to the tropical forestry scene. For all its newness however, its pest status has rocketed from pretty much unknown in 2004, to global problem 10 years later. Mendel et al. (2004) recorded *L. invasa* as a new genus and species of gall-forming hymenopteran in the family Eulophidae. Only females were identified at the time, but the galls their larvae caused to occur on leaves and petioles were already having significant impact on *Eucalyptus* species in the Middle East and Africa. Zheng et al. (2014) listed 29 countries where the pest has established. These include Brazil (Garlet et al. 2013), India (Senthilkumar et al. 2013), Morocco (Maatouf and Lumaret 2012), Iraq (Hassan 2012), Argentina (Aquino et al. 2011), Taiwan (Tune and la Salle 2010), and China (Wu et al. 2009). Most damage is done to seedlings and young trees (Zhu et al. 2013a), and impacts vary. In Sri Lanka, for example, Karunaratne et al. (2010) found that 10 % of coppiced *Eucalyptus camaldulensis* suffered heavy damage, whilst 62 % suffered low (but not zero) damage. These figures need to be verified across the world and between tree species and then converted into yield and monetary losses.

Effective control is likely to be particularly difficult because of large populations, small body size, overlapping generations, and the concealed nature of the pest larvae inside galls (Zhu et al. 2012). However, management tactics may take the forms of a series of measures itemized below:

(a) Avoidance – nonimport and quarantine

It is probably too late to prevent *L. invasa* reaching most of the countries where eucalypts are grown. The pest has undergone huge range expansion in the last decade or so (Ramanagouda et al. 2010), and it is now a very serious invasive species for which quarantine will be ineffective.

(b) Host–plant relationships – planting sites and resistance

Because of the rapid appearance of this pest, certain crucial items of information are so far lacking. Whether or not it prefers stressed or healthy trees has yet to be established and its associations with altitude, water relations, climate regimes etc. are also poorly understood. Obtaining such details will be a key in any attempts to establish IPM tactics. We do know that the pest is less of a problem in drier seasons (Nyeko et al. 2010), but this is fairly typical of many herbivorous insects.

Field trials to look for resistance to *L. invasa* across genotypes and species of *Eucalyptus* are also rather limited, but some results are available. Trials in Kenya and Uganda classified genotypes of *Eucalyptus henryi* as resistant to the pest, *E. dunii* as tolerant, *E. camaldulensis* as tolerant or moderately susceptible depending on germplasm, whilst *E. tereticornis*, *E. grandis*, and *E. saligna* were moderately or highly susceptible (Nyeko et al. 2010).



In India however, *E. tereticornis* was found to be maximally infested with galls and *E. grandis* less so. *E. urograndis*, a hybrid between *E. grandis* and *E. urophylla*, showed minimum infestations (Kumari et al. 2010). In China, highest susceptibility was shown by *E. urophylla* and *E. exserta*, with *E. tereticornis* and *E. robusta* being most resistant (Zhu et al. 2012), whilst Luo et al. (2014) suggested that taller trees tended to be less infested than shorter ones. Finally, in South Africa, the damage index for *L. invasa* was greatest on various hybrids between *E. nitens* and *E. grandis*, and *E. grandis* and *E. camaldulensis*, whilst zero damage indices were recorded on *E. dunii* and *E. grandis*, as well as a hybrid between *E. grandis* and *E. urophylla* (Dittrich-Schroeder et al. 2012). So, messages are unclear at the moment and more work must be done if reliable resistance properties can be employed in IPM programs.

(c) Trapping

Mass trapping as a tool for managing forest pests has rarely been successful because of its inefficiency at catching sufficient adult insects, though traps are routinely used as monitoring tools to establish if and when other management techniques should be deployed. In the case of *Leptocybe*, Kumari et al. (2010) employed sticky traps to catch flying gall wasps, and concluded that flat yellow traps coated in sticky gum impregnated with eucalyptus oil; gave the best results. Unfortunately, the researchers did not evaluate any resulting reductions in pest or damage incidence; Zheng et al. (2014) reiterate that sticky traps of various shapes and sizes could be used to catch adult insects and this reduced the size of the next generation.

(d) Biological control

Various natural enemies of *Leptocybe invasa* have been identified (Kulkarni et al. 2010, Ramanagouda et al. 2011). No predators or pathogens have been recorded in the literature, but quite a lot of parasitic hymenoptera are known to occur. Various genera of parasitoid have been identified which may prove useful in classical biological control release programs. These include *Selitrichodes* (Kelly et al. 2012) and in particular, *Megastigmus* (Sangtongpraow and Charernsorn 2013). Note of course that because pest larvae are concealed within their galls, discovery and subsequent oviposition by parasitoid female adults is likely to be slow. Nonetheless, in greenhouse trials, *Megastigmus* sp. were able to cause ~10 % parasitism of *L. invasa* which rose to ~23 % 10 months later and ~28 % a month after that (Kulkarni et al. 2010). In Sri Lanka, Udagedara and Karunaratne (2014) recorded a mean percentage parasitism of *L. invasa* of 67 %. Whilst not overly impressive numbers, especially since they would be likely to be lower under field conditions, it may be that an integration of this form of biological control with semiresistant host trees (and even mass trapping) might give some satisfactory control.

(e) Chemical control

Hemiptera such as *L. invasa* do not employ sex-attractant pheromones in the ways that Coleoptera and Lepidoptera do, and toxic insecticides are

unlikely to reach pest larvae inside galls. No reports are yet forthcoming concerning chemicals acting as repellants. In short, chemical control methods for this pest are not thought to have much potential.

So, IPM of *Lepto cybe invasa* may be possible using a combination of host tree resistance and biological control using parasitoids. A lot of pure and applied field work needs to be carried out before successful tactics can be found.

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## Future Trends

During the second half of the 20th century, tropical forestry has been in a phase of great expansion. The utilization of natural forest, its conversion to agriculture and forest plantations, and its management for sustained timber production have all gone on apace for both sound and unwise economic and social reasons. Unfortunately, it is quite apparent that the management of pests and diseases in managed natural forests and plantations is lagging far behind. Research is often inadequate to provide foresters with the advice they need, and more financial backing is required to provide this information. Even the taxonomy of many groups of forest pests and fungi is in its infancy. A further problem is to persuade tropical forest managers to use what knowledge is already available with experts being consulted at a very early stage before planting is attempted. The training of local scientists and forest workers in the fields of entomology, pathology, nematology, virology etc., is also lacking, hence many opportunities for the prevention of pest and disease problems are missed. Neither forest pathology nor forest entomology services should be entirely responsive to new pest and disease outbreaks, but should be based on sound planning and forethought with at least a minimum of infrastructure and trained personnel always at hand.

Within each discipline, the trend is already for chemical control to become more target-orientated, with the development of chemicals with greater specificity towards particular organisms. Similarly, greater use of biological control and integrated pest management will be made as our knowledge of pests and diseases becomes more detailed. These trends will also be greatly encouraged by the public and political awareness of environmental concerns. In addition, new breeding techniques, such as genetic engineering, offer great, albeit somewhat risky, opportunities for the development of trees resistant to pests and diseases. Molecular biological techniques also offer the opportunity for the development of rapid, highly accurate methods for disease diagnosis.

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