Monitoring and Prediction

Using the appropriate chemical or biological tactic in the right place at the right time without wasting labor and money, whilst still achieving successful control, is an IPM juggling act. Perhaps the most fundamental feature of IPM compared with conventional pest management tactics is the reliance on some form of monitoring procedure to tell the forester whether or not he or she can expect to have a pest problem in the future. Hence the luxury of IPM is the decision to take no action, safe in the knowledge that nothing economically serious is going to happen. It is crucial to note that no monitoring system can be regarded as reliable without impact assessments, risk or hazard ratings, and a knowledge of threshold densities (numbers of the lifestage counted above which significant pest damage can be expected). Various techniques, some more laborious than others, are used in forestry as monitoring systems, and **Table 13** shows some examples.

Conclusions

An IPM 'toolbox' may be imagined which contains all the elements of pest management discussed above. These include preventive systems such as site choice and species matching, as well as interventionist tactics such as chemical and biological control. Underpinning these tactics is a sound and reliable monitoring system with which management decisions can be made. Clearly, not all specific forest pest situations will require each of these tactics, and so the 'toolbox' concept can be applied whereby the various components appropriate to a particular problem (and its solution) can be used, leaving the rest for a different scenario.

See also: **Entomology**: Bark Beetles; Defoliators; Foliage Feeders in Temperate and Boreal Forests; Population Dynamics of Forest Insects; Sapsuckers. **Health and Protection**: Integrated Pest Management Practices. **Pathology**: Insect Associated Tree Diseases.

Further Reading

Speight MR, Hunter MD, and Watt AD (1999) *Ecology of Insects: Concepts and Applications*. Oxford, UK: Blackwell.
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Integrated Pest Management Practices

H F Evans, Forestry Commission, Farnham, UK
M R Speight, University of Oxford, Oxford, UK

Introduction

The principles of integrated pest management (IPM) (*see* **Health and Protection**: Integrated Pest Management Principles) require a comprehensive knowledge of the reasons for pest outbreaks and, further, an understanding of which processes can be manipulated to reduce the severity of any outbreaks. While the concepts of IPM are intuitively sound, the practical implementation of those concepts to reach a successful conclusion is not always so easily achieved. In fact, case studies to illustrate IPM successes in forestry are relatively few if a strict definition of 'integrated' is adopted, such that there is a requirement for a multifaceted approach across a range of disciplines. In reality, although there are multiple variables to contend with, management will tend to rely on one or two key elements to achieve pest reduction.

This article deals with case studies that have been selected to illustrate the principles of IPM in practice and also to illustrate how those principles are applicable in both temperate and tropical forest systems. In providing these case studies, it is clear that not all groups of insect pests can be included and, therefore, some emphasis is based initially on discussion of management tactics in a wider sense, followed by the specific case studies.

Options in Integrated Pest Management

Traditional pest management tends to rely on one or, occasionally, a low number of options for reducing the damage caused by a particular organism. Choices are driven by the economic threshold that can be tolerated and by how quickly the pest population must be reduced below the economic threshold. In some cases, there is little choice but to use direct intervention methods based on chemical pesticides and this is an option within an IPM strategy. However, the key advantage of IPM is assessment of a range of options and the choice of a combination of these to achieve pest reduction. IPM therefore requires a disciplined approach to decision making, taking account of the individual and combined effects of a range of options. Ideally, the choices will also be dynamic in that the strategies employed will change and evolve with the changing densities of the target pest. **Figure 1** illustrates a range of the steps required to develop IPM in forestry and distinguishes two complementary approaches to management, namely prevention and cure.

Although the actions involved in achieving these ends may be similar, the ultimate aim will be to develop prevention so that long-term, sustainable population management can be achieved. In reality, there is usually a balance between prevention and

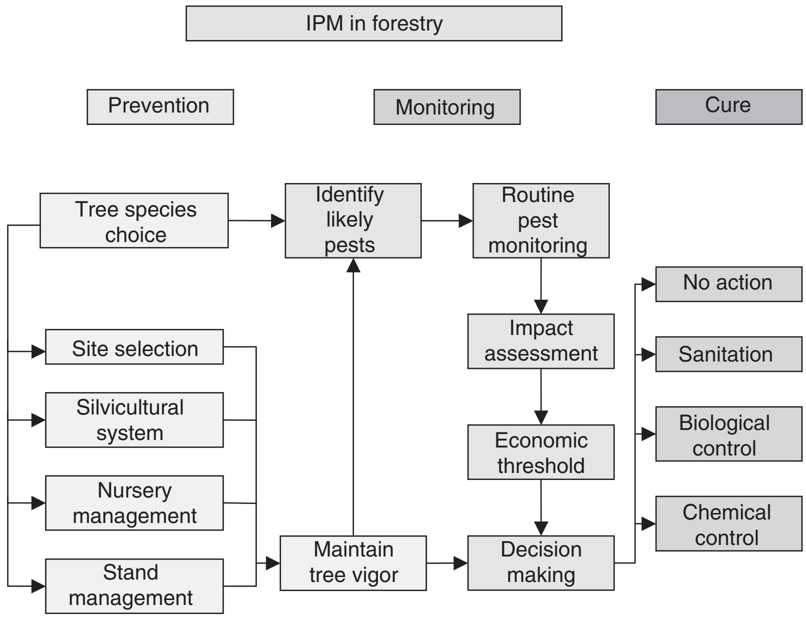

Figure 1 Schematic representation of the key components of integrated pest management in forestry.

cure, both of which depend on the quality of the monitoring and decision making components of the IPM system. Emphasis on maintaining tree vigor as a baseline component of an IPM system goes a long way towards achieving both prevention and, if there is an existing problem, cure.

General Management Tactics in Relation to the Feeding Strategies of Pest Insects

Insects are often classified according to the sites that are damaged during the life cycle. The majority of cases relate to the immature, larval, or nymphal stages of the particular pests. In part, this is determined by the processes employed by the adult pests to select suitable egg-laying sites that will lead to the highest likelihood of successful survival by their progeny. Consequently, the tactics employed to manage pests will be tailored to the types of feeding strategy by a given pest species. This is illustrated in **Figure 2**, which shows the four main categories of insect feeding strategy and some of the tactics employed to either prevent (a primary IPM strategy) or cure the problem.

Bark Feeders and Wood Borers

This group of pests is dominated by beetles (Coleoptera) but there are also significant representatives in the wood wasps (Hymenoptera) and moths (Lepidoptera). In the majority of cases the life cycle includes a period of feeding in the cambial layer of the inner bark which may occupy some or all of the larval feeding phase of the pest. Wood borers include an additional period during which the pest feeds in the sapwood or, occasionally, in the heartwood. Some, such as the wood wasps (in the hymenopteran family Siricidae) oviposit directly in the sapwood using a long ovipositor capable of boring into the wood.

The nature of these pests means that they spend the majority of their cycle in well-protected situations under the bark or in the wood itself. This makes it impractical or impossible to employ insecticides, although the use of systemic insecticides (those taken up by the roots of the plant) is being employed to attempt eradication of the Asian longhorn beetle (*Anoplophora glabripennis*) in the USA. An IPM approach, therefore, concentrates on understanding the nature of the interaction with the host tree and making use of the natural defenses of trees to prevent successful attacks. Thus **Figure 2** concentrates on prevention by matching trees to the site both in terms of tree species and of the mixtures and ages of trees that are present on site. There is considerable variation in the susceptibility of tree species and of the seed origins of particular species in relation to the ability of bark and wood borers to successfully attack trees. Defenses are usually manifested in aspects such as the nature and quantity of resins/sap produced (poisonous and sticky), bark thickness, presence of inedible stone cells (lignified tissue) and poor nutritional value. Healthy, vigorous trees have increased levels of defensive traits and it is possible, over the long term, to select or breed tree species with improved resistance to insect attack. Usually, however, we only realize how effective these defenses are when trees are damaged or stressed in some way and

MANAGEMENT TACTICS – BARK FEEDERS AND BORERS

PREVENTION
- Match tree species to site
- Avoid soil aridity or waterlogging
- Avoid overmaturity
- Avoid root damage in nursery
- Avoid log piles, etc. near stands
- Avoid pruning/brashing/extraction damage

CURE
- Injection with systemic insecticide for high-value trees
- Remove infested material from site before re-emergence of pest
- Change tree species mix/age structure to favor less susceptible species/age

MANAGEMENT TACTICS – DEFOLIATORS

PREVENTION
- Avoid preferred tree mixtures
- Avoid highly susceptible provenances

CURE
- *Nurseries* – local spray of insecticide only when serious leaf loss is observed
- *Plantations* – plant less susceptible species/provenances
  - change tree species mix/age structure to favor less susceptible species/age
  - Apply microbial insecticides
  - Use mating disruption to reduce breeding success

MANAGEMENT TACTICS – SAP FEEDERS

PREVENTION
- Avoid nonvigorous trees (see BORERS)
- NB – prophylactic spraying in nurseries should **not** be carried out
- Avoid highly susceptible provenances

CURE
- *Nurseries* – local spray of insecticide only when serious leaf loss is observed
- *Plantations* – plant less susceptible species/provenances

MANAGEMENT TACTICS – ROOT FEEDERS

PREVENTION
- *Nurseries* – Avoid root damage
- *Plantations* – Reduce availability of breeding resources for weevils
  – Encourage alternative non-crop food sources
  – Incorporation of insecticide granules in planting hole if termite losses are high

CURE
- *Nurseries* – Soil drench of insecticide for white grubs, cutworms if losses serious
- *Plantations* – plant less susceptible species/provenances

Figure 2 Management tactics for the four main categories of pest feeding strategy.

then become highly vulnerable to attack. For example, wind not only destroys trees directly but also weakens standing trees to make them more vulnerable to attack by bark and wood boring beetles. Fluctuations of the eight-toothed spruce bark beetle *Ips typographus* in European spruce forests tend to be linked to episodes of tree stress that allow the beetle to build up in weakened trees before commencing attacks on the remaining living trees. Wind damage in France in the early part of the twenty-first century not only resulted in massive destruction from the wind itself but also ongoing destruction from the enormous populations of *I. typographus* that built up on the weakened and freshly killed trees. This has knock-on effects that are not confined to the area where the problems occurred initially. *Ips typographus* can be moved in wood with bark still present to other areas of the world where it is not native, thus posing a threat to those countries; this tends to increase during an episode such as that just experienced in France.

Prevention is, therefore, a practical proposition in relation to ensuring that trees are as healthy and vigorous as possible. Cure is also feasible, although this tends to require rapid action to prevent the pest populations from building up to epidemic proportions. A simple 6-week rule is used in many countries, including the UK; felled or damaged wood must be removed from site within 6 weeks of origin. This strategy acknowledges that the trees will be attacked rapidly but, by removing them quickly before the beetles are able to complete a full generation, the numbers of emerging adults on site is reduced significantly. Of course, the material taken off site must be processed quickly to prevent the movement of the pest to a new location.

In the longer term, restructuring of a forest may offer the ultimate management tool to keep bark and wood boring beetles within acceptable damage thresholds (this will be discussed in more detail in relation to the mountain pine beetle, *Dendroctonus ponderosae*, later in this chapter). However, the general principles are based on knowledge of the factors that encourage epidemic beetle populations. In the cases of bark beetles, this is often linked to the stocking densities and ages of the trees in a forest. For some beetles, high stocking densities, contiguous presence of trees, and an even age structure will be favored; this is the case for *I. typographus*, which sustains high populations in large contiguous forest blocks. Other beetles tend to attack older, overmature trees that offer thicker bark and tend to be less vigorous than younger trees. This is the case for mountain pine beetle and other *Dendroctonus* species.

The above examples are concerned with beetles that attack and kill living trees. However, economic damage can also be suffered as a result of secondary effects of bark and wood boring beetles. This is manifested in staining of wood as a result of fungi introduced by the beetles during attack and also the opening of the wood surface to colonization by saprophytic fungi and other organisms in the environment. This is generally a cosmetic degrade in that, provided the wood is harvested within a few months of attack, there is no loss of structural value but the wood tends to be downgraded because of its visual degradation. Wood borers also cause loss of value as a result of downgrading of wood quality resulting from presence of grub holes in the wood, often accompanied by fungal staining. In most cases, unless the attack is particularly severe, there is no significant loss in timber strength. The 6-week rule is effective against these organisms, although the introduction of staining fungi at the time of beetle attack and oviposition makes it difficult to prevent this form of degrade. General forest hygiene can help, but this has to be balanced against the desire, in relation to enhancing biodiversity, to retain deadwood in forests.

Defoliators

As the name suggests, defoliators damage trees as a result of feeding on the leaves. Their effects on the tree can range from cosmetic through to complete defoliation and death. Severity varies with the type of tree being attacked and on the time of year, relative to the growth cycle of the tree, when the attack occurs. For example, in temperate conifer forests the degree of damage and tree mortality is dependent on whether the pest attacks soon after bud burst and on whether it restricts its feeding to the older foliage or includes the current year's growth as well. In Britain the introduced lodgepole pine, *Pinus contorta*, is attacked by a range of defoliators that are normally associated with the native Scots pine, *P. sylvestris*. The European pine sawfly, *Neodiprion sertifer*, attacks older foliage on young trees and can completely strip that resource from the tree, leading to significant loss of tree growth. However, because it does not attack the current growth, trees normally survive even repeated episodes of defoliation. By contrast, attacks by pine beauty moth, *Panolis flammea*, include both the current foliage and, later, the older foliage and can lead to extensive tree mortality. Both the sawfly and the moth are sensitive to the seed origin of the lodgepole pine and this can be exploited, at least in part, to reduce the severity of attacks. More northerly provenances, particularly Alaskan origins, tend to have much higher levels of tolerance. Restructuring of the forest is also effective, particularly against pine beauty moth. In this case, switching to Scots pine results in lower levels of attack, partially linked to tree quality but mainly due to the greater presence of natural enemies associated with Scots pine. Thus an integrated approach would be to increase the proportion of Scots pine in a forest block and to include open spaces and an uneven age structure to attract and retain natural enemies, particularly small mammals that feed on the overwintering pupae in soil. Direct intervention is also feasible for most forest defoliators, with the preference being for application of microbial pesticides of which *Bacillus thuringiensis* (*Bt*) is the dominant agent. This has been used extensively in both Europe and North America and in an unusual case, for complete eradication of an imported moth (white marked tussock moth, *Orgyia thyellina*) in an urban situation in Auckland, New Zealand. *Bt* is the agent of choice for gypsy moth (*Lymantria dispar*) in Europe and North America, for spruce budworm (*Choristoneura fumiferana*) in North America, and for nun moth (*Lymantria monacha*) in Europe. It is normally applied from the air and, increasingly, is applied using sophisticated spray technology that enables effective targeting and minimal loss to non-target areas. It is relatively specific in its action and is regarded as environmentally sound. Even more specific microbial agents are found among the baculoviruses that tend to be monospecific or restricted to a few species within given genera. They have proved effective against both temperate (e.g., pine beauty moth, pine sawfly, gypsy moth) and tropical (e.g., teak defoliator moth, *Hyblaea puera* – see case study) pests. In all cases, precise timing to deliver the agent to the most susceptible larval stages is essential to ensure the highest mortality and most rapid kill. The drawbacks of using baculoviruses relate, ironically, mainly to their high specificity so that each pest requires a specific facility to produce the virus, usually *in vivo*. However, the environmental benefits are very high and, in some cases (e.g., pine sawfly) the virus can maintain natural epizootics once introduced and, therefore, reduce or eliminate the necessity for multiple applications.

Sap Feeders

Sap feeders are predominantly in the order Hemiptera, which includes adelgids, aphids, cicadas, leafhoppers, plant bugs, plant hoppers, psyllids, scale insects, and whiteflies. Both the adult and immature (nymphs) stages feed on sap by inserting their specialized sucking mouthparts (stylets) into the phloem or sometimes xylem (in the case of cicadas) of virtually any part of the tree but predominantly buds, leaves, or in some cases, bark. Damage can be severe and can occasionally lead to tree death. In most cases the trees survive but there may be secondary effects in making the trees vulnerable to attack by other pests and in the production of honeydew, a sweet waste product that is then colonized by fungi such as sooty molds. This can be both unsightly and further restrict tree growth by reducing photosynthesis due to coverage or remaining foliage.

IPM of sap feeders is similar to bark feeders and borers in that trees that are nonvigorous are more vulnerable to attack and, therefore, should be avoided. Similarly, there are large variations in the genetic susceptibility of trees to attack and careful selection of tree species, seed origins, and mixtures should help to reduce the severity of infestation. It is not practical to consider use of insecticides in plantation forests both because of the environmental impacts but also because of the rapid recolonization that tends to take place that would tend to require reapplication at relatively frequent intervals. However, sap feeders are also problems in nurseries and, in these situations, it is possible to consider emergency applications of insecticides to supplement any other measures such as encouragement of natural enemies and use of vigorous, more resistant species and seed origins.

Root Feeders

By their very nature as feeders in a hidden environment, this category of pest tends to be less studied, particularly from the point of view of delivering IPM through detailed knowledge of the factors leading to pest outbreaks. Within this group there has been most emphasis on pests at the nursery stage of production, where both the impacts and identities of the pests are easier to record and develop strategies for management. In temperate areas, root damage tends to be linked to beetle or lepidopteran larvae in the main. Weevils, especially in the genus *Otiorhynchus* (the vine weevil, *O. sulcatus*, being the best-known European example) and chafers, including the genera *Melolontha* and *Phyllopertha*, tend to be the most damaging. Cutworms in the lepidopteran family Noctuidae are also serious pests in that the larvae are soil dwelling and can browse both on the root collar and on the plant itself. Other pests include bibionid flies in the genus *Bibio* and nematodes, especially *Dolichorhynchus* spp. Tropical pests in this category include termites and white grubs (Coleoptera: Scarabaeidae).

Impacts in plantations can be serious but, not surprisingly, the cause can be overlooked because of the cryptic nature of the niche occupied by the pests. Young plants can be affected by the majority of pests associated with forest nurseries, with the addition of some root dwelling aphids, gall wasps, and bark beetles. In such situations, the key to success is reducing breeding resources for the pests as well as intervention using chemical or microbial pesticides in extreme cases. However, there has been relatively little work on this group of pests and it is likely that their impacts are often not recorded or underestimated.

Case Studies

Within the large array of forest pests in both temperate and tropical forests, there has been relatively little development of IPM from first principles (*see* **Health and Protection**: Integrated Pest Management Principles). However, it is possible to illustrate how approaches that fulfil the aims of IPM have evolved for selected temperate and tropical pests. We have, therefore, selected examples from temperate and tropical forestry to cover only two of the main feeding strategies discussed earlier, i.e., bark feeders/wood borers and defoliators.

Great Spruce Bark Beetle, *Dendroctonus micans* (Coleoptera: Scolytidae)

This is a serious pest of spruce throughout its range in Eurasia (**Figure 3**). However, as indicated in **Table 1**, the beetle can be managed successfully using IPM principles, with particular emphasis on early detection and introduction of the specific predatory beetle, *Rhizophagus grandis* (Coleoptera: Rhizophagidae) (**Figure 4**).

Great spruce bark beetle is somewhat unusual in its attack strategy compared with some of the more damaging, aggressive bark beetles that are also in the

Figure 3 Adult great spruce bark beetle, *Dendroctonus micans*. Photograph courtesy of Forestry Commission Research Agency.

Table 1 IPM of great spruce bark beetle, *Dendroctonus micans*

Great spruce bark beetle, Dendroctonus micans	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
A dangerous pest of spruce trees in northern temperate forests from Asia to western Europe. It attacks living spruce trees causing damage to the main stem and large branches and can kill trees during outbreaks.	Depending on location and average temperatures, the beetle has a life cycle that lasts from 12 to 24 months. Generations are not synchronized and eggs, larvae, pupae, or adults can be found at any time of the year. Females excavate an egg gallery in the living bark, each laying up to 350 eggs. Larvae feed communally, responding to a larval aggregation pheromone, which is a mechanism to enable them to withstand the sticky and toxic resins produced by the tree as a defense against attack.	Regarded as a serious pest of spruce in newly colonized forests and in forests where trees are particularly vulnerable to attack. It is a solitary bark beetle that completes its life cycle in living trees without the need for mass attack to overcome tree defenses. There is no adult aggregation pheromone or associated symbiotic fungi to overcome tree defenses.	Overmature, stressed, or damaged trees are more vulnerable to attack, but even apparently fully healthy trees can be colonized successfully. Trees planted on unsuitable soil types are particularly vulnerable to attack, e.g., Sitka spruce planted on relatively sandy soil in Denmark were attacked and killed by great spruce bark beetle.	1. Surveys to detect infestations, especially during early colonization in previously uninfested forests. This is particularly important in forests geographically isolated from known infestations and which may not have been colonized by the specific predator *Rhizophagus grandis*. 2. Selective felling to reduce or remove incipient populations in a newly infested forest or to reduce expanding populations in forests lacking *R. grandis*. Felling concentrates on removal of overmature or damaged/stressed trees, but avoiding further damage to remaining trees. 3. Restriction of timber movement to reduce the likelihood of infested timber being moved to uninfested forests. This applies particularly to those regions where *D. micans* is a new incursion (e.g., Great Britain, Massif Central in France) and where active management to contain outbreaks is being carried out. 4. Biological control using the specific predatory beetle *R. grandis*. This is a natural associate of *D. micans* throughout the majority of its Eurasian range. However, new incursions of the bark beetle will tend not to have the predator present and mass rearing and release strategies have been developed. The predator has been successfully introduced to the Georgian Republic, southeast France, Great Britain, and Turkey and is a key component of an IPM system.

genus *Dendroctonus* (see mountain pine beetle below). Females mate with males in the same brood chamber prior to emergence as mature adults. This, combined with the very high bias towards females in each generation (as high as 40 : 1 female : male), means that each female is immediately capable of attacking a host tree without recourse to attracting a male. In addition, the beetle is very well adapted to withstanding the copious resin flow that is characteristic of wounded spruce trees. It is not, therefore, necessary for the beetle to use mass attack strategies to establish a successful brood, nor does it require the added factor of an associated fungus to help overcome tree defenses. Thus, it is a relatively solitary bark beetle in which each female can establish a successful colony. This may, at least partially, explain why it has been able to expand its range westward into previously unattacked regions of Europe; it has established in the Georgian Republic, southeast France, Turkey, and Great Britain during the latter half of the twentieth century.

IPM strategies that have been adopted across Europe have included surveys to establish the extent of new infestations and then, dependent on the extent of the infestations, a number of options for management. In some cases, sanitation felling, including complete removal of forest blocks, has been carried out. This tactic reduces population pressure on remaining uninfested trees and, depending on the timing within the normal rotation of the crop, may

Figure 4 Larvae of the specific predator, *Rhizophagus grandis*, feeding on larvae of their prey, *Dendroctonus micans*. The predators feed gregariously and leave the empty husk of their prey behind before moving on to the next prey item. Photograph courtesy of Forestry Commission Research Agency.

only have a small impact on revenue achieved. However, in areas where both timber products and ground stabilization are management aims, early felling is not a viable option. In some cases, particularly in Great Britain, discovery of new infestations has been early enough to establish a containment regime such that movement of felled timber from known infested areas is regulated so that only wood that has been debarked is approved for transportation to uninfested parts of the country. The latter, under European Union rules, has been designated a Protected Zone and, at least in Great Britain, appears to have successfully restricted long-distance dispersal of the pest for the 21 years since the strategy was adopted. Natural spread, by beetle flight, still takes place, however, and this has been at a rate of 3–5 km per annum in the British outbreak. As part of the IPM strategy, a peripheral zone survey has been carried out annually and this has both quantified natural spread and also enabled new pioneer populations of the beetle to be managed by a combination of selective felling and further introductions of the predator *R. grandis*.

The cornerstone of an IPM approach to great spruce bark beetle is rearing and release of *R. grandis*. This predator is specific to *D. micans* and has been released with great success in all the new infested areas in Western Europe. In Great Britain, a program of releases was initiated in 1985 and has continued annually since then by concentrating on new infestations found on the periphery or in new areas remote from the main infested zone. For example, a completely new infestation was found in Kent, well to the east of the known infested area and this has also been successfully treated with *R. grandis*.

Overall, the combined strategy for great spruce bark beetle has been remarkably successful in all locations where predator-based IPM approach has been adopted. In relation to other bark beetles, this example is unique in that silvicultural management is not the main component of an IPM approach. This contrast is well illustrated by the mountain pine beetle example discussed below.

Mountain Pine Beetle, *Dendroctonus ponderosae* (Coleoptera: Scolytidae)

Mountain pine beetle is one of the complex of *Dendroctonus* species that affects conifer forests in North America. Within the current range of the pest in western North America, it is regarded as one of the most destructive, with particularly heavy attacks and tree mortality being observed on lodgepole pine, although other pines are affected to a lesser extent.

By contrast to the European relative *D. micans* discussed above, this species adopts an aggressive attack strategy that relies both on weight of numbers and on an associated fungus to overcome the resin defenses of living trees. Low-level populations of the beetle are maintained by opportunistic breeding in weakened and dying trees, brought about through a range of biotic and abiotic factors. For example, wind or fire damage can reduce tree defenses sufficiently for even small populations of the beetle to build up. These populations may be large enough to become aggressive and to mass-attack living trees in the vicinity, leading to further attacks in a positive feedback loop. This can result in enormous population increases and spread of the pest over large areas.

Extensive research into the factors that lead to population outbreaks has been carried out, culminating in a sophisticated decision support system based on sound IPM principles. This can be accessed on-line from the Pacific Forestry Centre in British Columbia, Canada which offers a range of mountain pine beetle planning tools, including an excellent risk rating computer program. The key elements are described in **Table 2**. It appears from the information gathered on the pest, that the problem is partially man-made in that there has been a tendency for retention of older age classes of trees, by a combination of avoidance during felling and through implementation of fire suppression programs. Stand age is one of the key elements of the stand susceptibility index (SSI), which is made up of the following components:

$$\mathrm{SSI} = A \times D \times P \times L$$

where A is stand age, D is stand density, P is percentage of susceptible pine, expressed as basal area, and L is location (latitude, longitude, elevation).

The factors are described briefly in **Table 2** but, as a general rule of thumb, trees greater than 80 years

Table 2 IPM of mountain pine beetle, *Dendroctonus ponderosae*

Mountain pine beetle, Dendroctonus ponderosae	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
The most destructive pest of mature lodgepole pine trees in western North America. Western white pine and ponderosa pine can also be attacked. Outbreaks develop rapidly and can result in very large areas of trees being killed within a relatively short time period. It mainly attacks living, older, large-diameter trees (overmature), with initial attacks in stressed, unhealthy trees.	Over most of its range, mountain pine beetle has a 1-year life cycle, although this may extend to 2 years at high altitudes and in the northern part of its range. Larvae overwinter and recommence feeding in the spring to pupate and emerge as adults in mid to late July. Adults range in size from 3.5 to 6.5 mm. Initial attacks are by females that bore into the bark and, once established, produce an aggregation pheromone that, initially, attracts females then males. Mating occurs under the bark, after which the females bore vertical egg galleries in which eggs are laid in niches on the sides; up to 75 eggs are laid per gallery, but females can produce up to 260 eggs. Eggs hatch quickly and larvae feed at right angles to the axis of the egg gallery. They feed until winter, usually reaching 2nd or 3rd instar.	A highly destructive bark beetle that initially attacks weakened trees, but then uses mass-attack strategies to overcome apparently healthy trees. The beetle carries a blue-stain fungus that also contributes to overcoming tree defenses and, combined with larval feeding in the cambium, can lead to tree death. Losses arising from attack by the beetle can be enormous; during the period 1997–2002 an area of 9 million ha was affected in British Columbia, leading to losses of 108 million m^3.	Risk rating systems have been developed for mountain pine beetle. These offer the prospect of managing outbreaks by reducing the risk factors. The key factors are: 1. Stand age. Beetles prefer older trees which are less resistant and, being bigger, are easier to locate. 2. Stand density. Beetles prefer moderate densities which offer suitable bark thickness and only moderate tree defenses. Microclimate is favorable to the beetles. 3. Percent susceptible pine (basal area). Beetles prefer large trees with thicker bark and well-developed phloem that provides protection and ample breeding resources. Higher stand densities reduce searching time for new host trees. 4. Location factor. Beetles are more successful when temperatures support a 1-year life cycle. This factor is driven by latitude, longitude, and elevation.	1. Stand susceptibility index. A product of the four risk factors. This is a component of the mountain pine beetle decision support system which uses susceptibility ratings for longer-term forest management. A computer model has been developed to aid this process and is freely available from Natural Resources Canada. 2. Risk index. Beetle pressure is a function of the size and proximity of beetle populations to the stand being assessed for management. This is based on the relative size (small, medium, or large) of the beetle infestation within 3 km of the stand at risk. This information is then used in a lookup table for distance to the nearest infestation to derive a beetle pressure index. Together with the stand susceptibility index, this is combined to give an overall risk index between 0 and 100. 3. Reduction of stand risk through IPM. Stand susceptibility can ~be altered through silvicultural management, with the aim being to break up large, homogeneous stands predominantly composed of large highly susceptible trees. This requires selective felling to thin 'from above' thus lowering average age, size, and stand densities towards an acceptable susceptibility index. Beetle pressure is not so easily managed but includes factors such as sanitation logging and debarking, fell and burn, or possibly insecticide use.

old and stand densities from 751 to 1500 stems ha^{-1} are intrinsically the most susceptible. Combined with the proportion of pines with diameters >15 cm, but especially >40 cm, and a factor to reflect temperatures calculated from an equation for longitude, latitude, and elevation, an overall SSI from 0 to 100 can be calculated, with 100 being the most susceptible. Further assessment of risk includes a beetle pressure index (B) derived from lookup tables for size of infestation (small, medium, or large) and distance from the nearest infestation, ranging from within the stand to >4 km away. A value of $B = 1$ indicates a large infestation within the stand, whereas a value of $B = 0.06$ represents a small infestation >4 km from the stand.

Prior assessment of risk is a key tool in longer-term management of the threat posed by mountain pine beetle. Prevention can be achieved by working towards a reduction in the SSI towards a nonsignificant value. This can be achieved by controlling the stocking density in young stands as part of planning for future protection. In older stands, SSI reduction can be achieved by specific thinning, particularly of larger diameter, older trees combined with felling to reduce the proportions of pine within stands. Naturally, care must be taken in restructuring stands to avoid 'high-grading,' which could leave only inferior trees that have lower silvicultural and environmental values and be more vulnerable to abiotic factors such as wind and snow damage. Careful management of stands to reduce stem densities below $750\,\mathrm{ha}^{-1}$ can still achieve an acceptable SSI and leave sufficient larger, old pines for biodiversity interest.

If it is not possible to prevent beetle build-up, then a number of direct measures can be employed to manage and reduce the beetle outbreaks. These include rapid removal of infested material to prevent re-emergence of the pest. Fell and burn, treatment with insecticides, mechanical debarking, and sanitation felling can all achieve these ends, although they can be difficult logistically. Use of semiochemicals to attract beetles to trap trees or to traps placed away from the potential host trees has also been employed, with some success.

Pine Beauty Moth, *Panolis flammea* (Lepidoptera: Noctuidae)

Pine beauty moth has a long history as a pest of Scots pine, *Pinus sylvestris*, in continental Europe where it has periodically resulted in severe defoliation and tree mortality. By contrast, the moth is not regarded as a pest on Scots pine in Great Britain, where it remains at low levels on this tree species throughout the country. The appearance of large, outbreak populations of *Panolis flammea* on the exotic north American lodgepole pine, *Pinus contorta*, in Scotland during the 1970s was, therefore, a surprise. However, it also illustrates, in a converse way, one of the key principles of an IPM approach to pest suppression because the planting of an exotic tree species on marginal sites presented the moth with a situation in which key factors preventing population build-up were absent (**Table 3**). Specifically, trees were planted on deep, poorly-drained peat soils that provided ideal conditions for overwinter survival of the pupal stage and were also relatively impoverished with regard to presence of natural enemies.

The moth outbreaks were worse on deep peat sites over moine schist underlying rocks and, within the seed origins of lodgepole pine, were more serious on southerly provenances. This combination of high suitability as a larval food source and the enhanced overwinter survival led to rapid population increases that outstripped the available food supply in some forests, leading to a population crash but only after the host trees had been killed. Research into monitoring methods and aiming also to establish the economic threshold for lethal attack, indicated that when densities of pupae, determined by pupal surveys carried out during the winter months, exceeded $15\,\mathrm{m}^{-2}$, tree mortality was likely. Further assessment of risk was carried out by egg surveys on trees in the same vicinity as the pupal surveys. When densities exceeded 600 eggs per tree, lethal damage was very likely and decisions on direct intervention had to be made. Surveys using the sex attractant pheromone of pine beauty moth provided useful corroborative data of population trends, but were not accurate enough or sufficiently in advance of egg hatch to allow control operations to be organized.

Early work on direct control of the moth concentrated on low-volume aerial application of the chemical insecticide fenitrothion. Although this was generally effective, considerable effort was put into finding more effective application technology, such that ultra-low-volume controlled droplet application is now the only method used for aerial application in Britain. This methodology employs spinning disc or spinning cage technology to deliver droplets within a relatively narrow range of sizes and which are captured by the target canopy zone with an efficiency exceeding 90%. Intervention has been carried out several times in Scotland, mainly using the insect growth regulator diflubenzuron delivered at volumes of $1\text{–}4\,\mathrm{l\,ha}^{-1}$. Tests with baculoviruses also proved effective, although the registration for the viral agent in Britain has lapsed.

In the longer term, management of pine beauty moth is likely to include choice of tree species and avoidance of particularly susceptible soil types. Mixtures of lodgepole pine with other conifer species will provide partial reductions in susceptibility, particularly when Scots pine, with a higher level of associated natural enemies present, is planted in mixture. Avoidance of highly susceptible provenances will also reduce the likelihood of lethal populations developing.

Teak Defoliator Moth, *Hyblaea puera* (Lepidoptera: Hyblaeidae)

Teak defoliator moth is the most important of a number of moths associated with teak and other trees and shrubs in the Orient and Australasia (**Table 4**). It is characterized by very rapid development, leading to multiple generations each year, depending on the average temperatures at a particular location. Although generations overlap at a regional scale,

Table 3 IPM of pine beauty moth, *Panolis flammea*

Pine beauty moth, Panolis flammea	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
A pest of older Scots pine in continental Europe and, although present at low levels on Scots pine throughout Great Britain, has become a pest of the introduced North American lodgepole pine (*Pinus contorta*) in Scotland. Extensive outbreaks can lead to tree mortality, especially on deep peat sites.	The moth has a singe generation per year which commences with adult emergence in the spring, usually in March or early April, followed by oviposition up to May. Egg hatch occurs by around mid-May, after which larval feeding commences in the current year's foliage. Later instars (3rd to 5th instar) feed on older foliage so that large moth densities can result in complete defoliation. Larvae drop to the forest floor to pupate in July and remain in the litter–soil interface until the following spring. Females produce a sex pheromone to attract the males.	Although pine beauty moth is a periodic and serious pest on Scots pine in Europe, with records of major outbreaks in Germany, Finland, Norway, and Sweden, it is innocuous on this tree species in Great Britain. Outbreaks leading to extensive tree mortality were noted on lodgepole pine in Scotland during the 1970s and have recurred periodically at 7–8-year intervals since that time.	In Britain the main risk factors are tree species and site type. 1. Tree species. As indicated above, outbreaks have been confined to lodgepole pine, which also shows considerable variation in susceptibility to infestation depending on seed origin. Thus, more southerly origins, such as Skeena River and South Coastal are more suitable hosts than northernly origins, such as Alaskan or North Coastal. This applies both to female choice for egg laying and to subsequent larval performance on the foliage. The low severity of attacks on Scots pine in Britain is linked to the greater action of natural enemies and the lower survival of pupae below Scots pine canopies. 2. Site type. Sites with deep, waterlogged peat soils support greater populations than other soil types, especially over the underlying rock type called moine schist. Although the trees themselves are not intrinsically more suitable, it appears that the underlying soil type is more suitable for pupal survival over winter.	1. Monitoring and economic thresholds. Monitoring of pupal numbers or adults in pheromone traps provides information on population cycles and also a threshold for possible direct control measures. Pupal densities of $>15\,m^{-2}$ are likely to result in severe defoliation or tree death. If this threshold is exceeded, egg surveys are carried out to determine whether populations have exceeded the threshold for damage on a local basis; the threshold is >600 eggs per tree. 2. Reduction of stand risk. Planting of Scots pine as a replacement for lodgepole pine will reduce risk considerably. If sites are not suitable for direct planting with Scots pine, then a mixture of lodgepole pine with Sitka spruce may reduce risk, but this is not sufficient to eliminate the likelihood of lethal attack. Selection of northerly seed origins of lodgepole pine is also a positive measure to reduce risk. 3. Direct intervention. If the economic threshold is exceeded, then direct intervention may be the only option to prevent tree mortality. The targets for intervention are the 1st and 2nd instar larvae and, therefore, timing of spray application to coincide with 95% egg hatch is a core part of pesticide application. Currently the only insecticide that is employed is the insect growth regulator diflubenzuron. Promising results have also been obtained in application of a baculovirus. In both cases, the use of sophisticated ultra-low-volume controlled droplet application systems ensures that sprays reach the target area in the top one-third of the tree, with little contamination of nontarget areas.

each population has a discrete center in which all the stages from egg, through larvae and pupae to emergent adults are well synchronized. Repeat attacks on the same trees are uncommon because moth populations migrate *en masse* to new locations.

Management of teak defoliator moth is dependent on early detection of infestations if any direct intervention is being contemplated. Remote sensing has not been developed and, therefore, surveys tend to be based on visual assessments by trained survey teams searching for early stages of defoliation. There has been some success in using light traps, particularly solar powered versions that facilitate sensing in remote locations without local power supplies.

Table 4 IPM of teak defoliator moth, *Hyblaea puera*

Teak defoliator moth, Hyblaea puera	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
A serious pest of teak trees (*Tectona grandis*) in India, Myanmar, Sri Lanka, Java, Papua New Guinea, Northern Queensland, Solomon Islands, West Indies, and East and South Africa. Although the moth causes extensive defoliation, trees are not usually killed but serious losses of growth increment have been recorded, especially in younger plantation teak. Attacks take place during the growth period of teak in the monsoon season and follow the northward progression of monsoons.	The moth has a very short life cycle, which can be completed in as few as 19 days but could extend to 36 days, depending on temperature. This can result in up to 14 generations per year. Each generation commences with swarming of the adults and migration to suitable host trees where they lay their eggs, singly on the under surface, on young leaves (i.e., tender leaves). Eggs hatch quickly and the young larvae feed initially on the under surface and later within a leaf flap cut by the larva at the leaf edge. Larvae pass through five instars and then drop to the ground to pupate. Emergence of adults is followed by mass migration to another site suitable for a further generation. This migratory behavior is not fully understood and makes it difficult to predict where the next infestation is likely to occur.	Loss of growth is the main negative characteristic of this pest. Up to 44% loss of volume increment has been recorded in young plantations up to 9 years old, while an overall loss of 13% volume has been quoted for the crop to rotation age at 60 years. The migratory characteristics of the adults and the very rapid development from egg through larvae to pupae make it very difficult to predict when or where the next outbreak is likely to occur.	There is a complex of factors that affects the likelihood of outbreaks occurring at both the local and the regional scales. 1. Flushing of teak. Teak does not grow during the dry season, although it will do so if availability of water is sufficient, as has been demonstrated in intensive plantation systems with drip irrigation. In natural and plantation forests, flushing of teak is coincident with the onset of monsoon rains and, therefore, breeding resources are regionally determined by the northward extension of the monsoon each year. 2. Proximity of alternative host plants. The moths are known to spend the dry season on food plants in the natural forest, of which 29 species have been recorded. Adult moths also rest on the foliage of non-food understory plants. It is thought that populations move from the natural forest to teak plantations when teak flushes in the spring. 3. Wind and migration. Mass migration of moths is linked to local wind conditions so that some sites, with well-defined wind directions, tend to have localized intense outbreaks while others where wind is more diffuse have distributed infestations.	1. Monitoring and economic thresholds. The migratory nature of teak defoliator moth makes it difficult to monitor the arrival of new populations for management decisions on direct intervention. Ground spotting using teams of trained observers has been employed in India with some success. This relies on rapid determination of infestations and the feeding back of information to managers. However, this is not a routine process. Use of light traps has also been studied and provides some promise for future monitoring. 2. Reduction of stand risk. It is known that some varieties and species of teak have early flushing, which could render them less susceptible to attack, e.g., varieties, known as 'Teli' ('oily') flush at least 1 month earlier than normal teak and appear to escape infestation. 3. Direct intervention. Although the moth is susceptible to a variety of chemical insecticides, most effort in India has concentrated on assessing the potential of microbial agents. Great advances have been made in isolation, production, and application of a naturally occurring baculovirus. Success in application of this agent depends on early detection of newly established populations.

Development of a full IPM system is in its infancy but work at the Kerala Forest Research Institute has thrown light on both population dynamics, migratory behavior of the adults and, with scientists from the Forestry Commission Research Agency, use of naturally sourced baculovirus applied using ultra-low-volume controlled droplet application technology. In this sense, there are interesting parallels to the management of pine beauty moth in Scotland, despite the enormous differences in generation times of the two moth species. Application of baculovirus in antievaporant oil formulations, but without any additional protection against ultraviolet light, has proved to be effective against 3rd instar larvae on standing teak trees. The targeting of this larval stage provides a longer window of opportunity for application and also takes account of the movement of the larvae over the leaf surfaces, which increases the likelihood of encountering lethal dosages of virus. On the basis of the results obtained in field testing, a virus production facility has been constructed by the Kerala Forest Research Institute to develop further the use of baculovirus as a key component of IPM of this important pest. Further work is needed to solve the difficult problem of development of an effective monitoring and tracking system for migratory moth populations. Remote sensing and use of geographical information systems (GIS) interfaces and predictive models offer prospects for success in the future, the principles of which will be applicable to other moths with rapid generation times and dispersal between generations.

Mahogany Shoot Borer, *Hypsipyla* spp. (Lepidoptera: Pyralidae)

This complex of moths poses the single most important threat to the commercial production of mahogany timber anywhere in the world. Apart from on a handful of isolated Pacific Islands, such as Fiji, all members of the mahogany group (Swietenoidea) within the Meliaceae are attacked the world over. Tree genera include *Swietenia* and *Cedrela*, indigenous to Central America, *Khaya* from Africa, and *Toona* from Australasia, and all are attacked to a lesser or greater extent both naturally, and especially when grown in plantations. The taxonomy of the moth is obscure. For at least 100 years, book after book has reported the existence of merely two species, *Hypsipyla grandella* in the New World, and *H. robusta* in the Old World (all the way from West Africa to the Solomon Islands). Unlike the spread of certain tropical forest pests from a recognized point of origin (see *Phoracantha semipunctata*, below), *Hypsipyla* is likely to be indigenous throughout its global range, and hence there are undoubtedly numerous genetically distinct populations that are likely to represent a number of species in relatively local areas. This is clear from the varied activities which *Hypsipyla* species can be found exhibiting; though shoot boring is the only direct economic damage, larvae indistinguishable from each other can be found attacking the bark, shoots, fruit, and flowers at various stages of development on the same tree (**Figure 5**). Such a varied but as yet unquantified genetic diversity has vital implications for general insect ecology, host–tree interactions, and of course pest management.

Figure 5 Larva of *Hypsipyla* attacking a shoot on a mahogany tree.

Figure 6 A mahogany tree distorted into a forked shape after being attacked by *Hypsipyla* larvae.

The economic damage is centered around the larva's tunneling up and down the leading shoot of trees up to 4 years or so old. The leader then distorts and/or dies, with the result that the young tree becomes bent, forked, or otherwise misshapen (**Figure 6**). Marketable high-value mahogany must consist of a straight, single stem for at least the first 4 m of height, and since this height is usually reached within 4 years or even less in most species in most locations, the key to the IPM of *Hypsipyla* is to prevent larval attack from the nursery stage until this age or height is reached. After that, any further damage to the tree is not economically significant, though mature trees may act as reservoirs of pests which are then available to attack individual young trees or whole new plantations in the vicinity. Despite this seemingly easy goal, realizing this aim has proved to be hugely intractable over at least 50 years of trying. This type of insect is a classically low-density pest, in that it takes only one larva per tree to destroy any economic value; tolerance of even a low pest density is not possible in any but a small minority of situations where trees such as *Khaya*

Table 5 IPM of mahogany shoot borer, *Hypsipyla* spp.

Mahogany shoot borer, Hypsipyla *spp.*	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
A pest of many species of tropical mahoganies of such magnitude as to preclude the commercial and sustainable production of high-quality timber in almost all countries throughout Central and South America, Africa, southern and southeast Asia, and Australasia. Effective IPM programs would have huge economic significance for many tropical countries.	Eggs are usually laid singly on the upper leaves or shoots of young trees from the nursery stage onwards. The hatching larva soon tunnels into a leading shoot, constructing a tunnel which may eventually extend for 10 cm or more. Copious sap and resin exudes from an entrance hole somewhere along the length of the tunnel, which binds together boring dust and frass produced by the larva into an easily recognizable orange or brown mass. Pupation usually takes place inside the tunnel. The whole life cycle takes 1 to 2 months, depending on tree species and climatic conditions, and single trees may harbor several larvae at different stages of development.	The leading shoot usually dies and several buds are produced near or around the damaged tip. One or more of the resulting laterals become dominant. An unblemished stem of at least 4 m is required, which takes a minimum of 3 or 4 years to achieve with most host trees, but attacked trees routinely end up stunted, dwarfed, bent, or forked, any of which renders them economically valueless. Prevention of larval establishment in tunnels in the shoots is vital, since the probability of killing larvae once inside before appreciable shoot damage occurs is very low. The natural ecology of the genus in tropical forests is essentially unknown.	Risks vary from country to country and tree species to tree species. 1. Tree species. A large number of species within the Swietenoidea are attacked, and reliable genetic resistance has been hard to find. Host species exotic to a particular country may be less attacked by the indigenous borer populations than native species. Some tree species are better able to tolerate shoot attacks and grow straight subsequently than others. 2. Age. Trees of all ages may be attacked. Individuals between 6 months and 3 years old seem to be most heavily attacked, but this is linked to site and tree species. If a tree can be grown pest-free for the first 4 years of life, direct pest management is no longer required. 3. Site type. Trees growing on dry or conversely clay soils are more likely to be attacked. Soil aridity or waterlogging both increase attacks. Well-drained but moist soils in high rainfall areas show fewest attacks. Sites at the bottom of valleys appear to support fewer forked trees resulting from borer attack as compared with those on slopes or at the tops of hills. 4. Planting conditions. Trees planted in the open with no overhead shade suffer most attacks, and individuals in these locations may suffer most repeated attacks. However, trees in the open grow most rapidly, but they may be attacked when taller and older than those in shade. Trees in the shade of other vegetation, whether natural or	Much more detailed information is required about the pest's natural ecology and host–plant interactions. Various IPM components based on risk averse tactics may however be attempted. 1. Tree resistance and choice of species. Exotic species or those with the ability to grow straight after an attack may be preferable, especially those showing strong apical dominance. Fast growth especially for the first 3 years is very important. 2. Choice of planting site. Shady conditions should produce a higher percentage of unattacked trees, though they will grow more slowly. This growth rate may be improved if moisture is available. In some situations, this may be the only way to produce a few marketable individuals. Dry or waterlogged sites must be avoided. Line or enrichment planting may be preferable to plantations. 3. Biological control. Predators, parasitoids, and even pathogens are likely to be inadequate for the prevention of attack, or to remove the pest when it has established. 4. Chemical control: insecticides. Routine and regular contact poisons may prevent attack for the crucial first few years, but it is highly debatable whether or not such tactics are economically or environmentally viable. Systemic insecticides from soil-applied formulations are not sufficiently effective. 5. Chemical control: pheromones, etc. Producing the appropriate cocktail of synthetic sex-attractant pheromones has so far proved impossible. Suitable compounds derived either from a sex-attractant, or possibly from tree fruit and flower volatiles, for monitoring and/or mating disruption, have potential in theory.

Table 5 Continued

Mahogany shoot borer, Hypsipyla *spp.*	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
			seminatural forest or an early cash or tree crop, grow more slowly but show a higher percentage of nonattacked individuals, and if attacked at all, very seldom more than once. The chance of recovery to a straight stem after attack is higher with plants growing in shade. 5. Location. New plantings of individual trees or whole plantations, in the vicinity of older plantations, or natural forest which contains members of the Meliaceae, are more likely to be attacked. Extreme isolation will remove high risks for a while.	6. Sanitation and pruning. When a small proportion of trees in a stand are attacked, complete removal and destruction may be tolerable, at the early stages of establishment at least. When more than one lateral shoot becomes dominant after an attack on an otherwise vigorous tree, pruning of all but one shoot may eventually produce an acceptable tree (especially *Khaya*).

anthotheca in Mozambique appear to be able to regrow a straight stem after recovery from certain types of attack.

IPM of *Hypsipyla* species has yet to be achieved commercially (**Table 5**). If and when commercially viable tactics are devised, they are likely to be relatively specific to certain geographical locations or individual tree species. A single solution which works over all the tropics is unlikely to be practical, though some general tactics may be fundamental to all IPM programs.

Eucalyptus Longhorn Beetle, *Phoracantha semipunctata* (Coleoptera: Cerambycidae)

Phoracantha semipunctata is a native of Australia which began to spread throughout the world wherever eucalypts were grown from the early 1900s onwards. It is now firmly established almost everywhere, from South and Central America (including parts of the southern USA), through Africa and parts of Asia, and into various countries of the Mediterranean region. All species of *Eucalyptus* may be attacked, as well as other members of the same plant family (Myrtaceae), but some species, such as the widely planted *E. grandis*, seem to be particularly prone to attack (**Table 6**). The key to which host species are most preferred is undoubtedly linked to their ability to withstand arid conditions – *Phoracantha* is a classic 'secondary' pest where the host tree has to be stressed in some way before colonization can be successful. Essentially, the more drought-intolerant a species, the more likely it is to be attacked by *Phoracantha* as soon as soil conditions lose moisture. This is a particular problem for regions with dry seasons where water stress for trees is an annual event.

Adults mate on the bark of suitable host trees, and the eggs hatch into larvae which burrow under the bark and feed and grow between the inner bark and the sapwood surface (**Figure 7**), in much the same way as the bark beetles described earlier in this section. As the larvae grow, and especially when multiple attacks occur in one stem, ring-barking or girdling of the infested trees occurs, and the host dies. Final instar larvae tunnel into the wood and pupate in chambers prior to emerging through characteristically flattened or oval-shaped exit holes. The links between drought-stress and insect success are complex, but seem to be associated with the facts that young larvae have difficulty tunneling into trees with active sap flow. Once established under the bark, there is a further problem for them in that trees with high bark moisture in well-irrigated sites support little or no larval survival. Protection is, therefore, supremely simple – never plant drought-intolerant eucalyptus species in regions or sites where the soils may dry out.

Conclusions

IPM as an approach to sustainable forest pest management has many attractions. In particular, it is a knowledge-based system that involves development of a deep understanding of underlying processes. We have placed the emphasis on prevention of pest outbreaks so that planning for pest management

Table 6 IPM of eucalyptus longhorn beetle, *Phoracantha semipunctata*

Eucalyptus longhorn, Phoracantha semipunctata	*Life cycle*	*Pest status and characteristics*	*Risk factors*	*Integrated pest management*
A very significant mortality factor for many species of *Eucalyptus* planted virtually anywhere in the world, but only if the trees are significantly influenced by dry or arid soil conditions. Vigorous trees in normal moisture conditions should be resistant.	The whole life cycle takes between 2 and 12 months, depending on the climate. Between 10 and 100 eggs are laid in bark crevices (coarser-barked species of *Eucalyptus* enable beetle eggs to be better protected from predation and parasitism). Larvae hatch after 2 weeks or so and colonize the inner bark/sapwood interface where they can feed and grow for several months. Tunnels are typically flattened and filled with tightly packed frass. Pupation in the wood itself may last 10 days. Adult lifespans may reach 90 days or more, giving the pest ample opportunity to seek out the flowers of healthy trees for energy, and then new suitable, stressed, host trees over a large area of territory. The most significant mortality factor seems to be competition for food and space in overcrowded larval populations; the effects of natural enemies are not so important if host conditions are suitable for the pest.	The species is secondary; vigorous, nonstressed trees are not at risk. Infested trees are typified by thin crowns, yellowing leaves or considerable leaf fall. Patches of bark may be loose and easily stripped off to reveal larval tunnels and the insects themselves. Older attacks are identified by the exit holes of newly emerged adults. The numbers of trees killed in a stand or a plantation varies considerably. The beetle is only a minor pest in Australia (though recently it has become more serious in Queensland), but in other countries, where both beetle and tree are exotic, mortalities can reach over 40%.	1. Tree species. The most susceptible species of *Eucalyptus* include *E. globulus*, *grandis*, *nitens*, *saligna*, and *tereticornis;* more resistant ones include *E. camaldulensis*, *cladycalyx*, and *sideroxylon.* It is important to note that some of the most susceptible species are also the most desirable from a silvicultural perspective. 2. Age. Once trees reach a size at which the bark is thick enough to support the tunneling of beetle larvae, attacks can be expected. Eucalypts on rapid growth sites will reach such a stage within a very few years. 3. Site type and planting conditions. Dry soils, arid conditions, seasonal droughts, etc., coupled with eucalypt species that are inherently drought-intolerant, are in high-hazard categories. Even planting in localities where soil aridity is not usually a problem can be risky, so that individual trees on the tops of ridges in shallow sandy soils can be expected to be at high risk of attack. 4. Forest management. Log piles or larger thinnings and brashings allowed to remain in forest stands may easily provide the pest populations with the resources to initiate successful breeding and then to move on to attack even temporarily stressed adjacent trees. Similarly, trees allowed to remain in the plantations beyond their optimal harvesting age (overmature trees) also pose a threat by providing breeding material for *Phoracantha*.	1. Tree health care. The promotion of tree health and vigor by strict adherence to the risk 'rules' above will virtually guarantee that *Phoracantha* is not a problem. However, the provision of sickly, drought-stressed trees is an accident waiting to happen. Cure, once the trees have been attacked, is almost impossible. 2. Tree species choice. Avoid all susceptible species wherever possible. Highly desirable growth or timber characteristics are only useful if the trees survive to reach harvestable age and size. 3. Stand sanitation. Remove or process all potential sources of adult beetles, such as infested trees (young and overmature), log piles, thinnings, unbarked cut logs, etc. 4. Biological control. Both egg and larval parasitoids of *Phoracantha* are known, and vigorous research programs are being pursued, in California for example, to promote biological control. So far, natural enemy impact has not reached levels where mortality is reduced commercially in high-risk situations.

is included from the outset of any forest operations, from planting to harvesting. Although success in pest reduction can be achieved at any stage of the crop, the options available tend to diminish as the crop matures. For example, choice of less susceptible tree species or provenances is only an option that can be controlled fully during the establishment phase of a crop. Thereafter, adjustment to the balance of species, ages, sizes, and spacings of trees are viable options, provided that the processes employed to adjust the variables are understood. In this respect, the case study on mountain pine beetle provides a

Figure 7 Larvae of *Phorocantha semipunctata* and the damage they cause to eucalyptus bark.

good example of effective use of detailed biological and silvicultural information in offering options for both prevention and cure. Of course, it may not be possible to put the choices into practice in all cases, either for economic or for logistic reasons and, therefore, a high element of flexibility is needed to implement successful IPM.

The increasing trend to reduce the use of chemical pesticides provides further impetus to strengthen knowledge-based management systems, although no options should be ruled out until all variables have been considered and their consequences assessed. IPM is, therefore, not a quick-fix solution to pest management, but can provide sustainable long-term pest prevention or suppression with only limited recourse to repeated intervention, particularly with chemical pesticides. We can expect it to be an increasing part of forest pest management in the future.

See also: **Ecology**: Plant-Animal Interactions in Forest Ecosystems. **Entomology**: Bark Beetles; Foliage Feeders in Temperate and Boreal Forests; Population Dynamics of Forest Insects; Sapsuckers. **Health and Protection**: Integrated Pest Management Principles.

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