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Forest pest management in a changing world

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The scope, context and science guiding forest pest management have evolved and are likely to continue changing into the future. Here, I present six areas of advice to guide practitioners in the implementation of forest pest management. First, human dimensions will continue to play a key role in most pest problems and should always be a primary consideration in management. Next, managers must recognize that it is practically impossible to use population suppression to prevent outbreaks that extend over large geographic regions. Silvicultural practices can sometimes be effective at reducing forest susceptibility to outbreaks but these methods should be based on sound science. Many of the most damaging forest pests are non-native species and minimizing the invasion problem is most effective when steps are taken early on in the invasion process. Furthermore, classical biological control and selection for host resistance are important approaches to managing established non-native pest species. Finally, plantations of exotic tree species, while often highly productive, are prone to catastrophic damage from invading pests.

Keywords: biological control; biological invasions; detection; eradication; forest health; quarantine; resistance; surveillance; silviculture

1. Introduction

In most regions of the world, the subject of forest entomology has undergone a vast transformation. During the period preceding World War II, most of the work by forest entomologists concentrated on three tasks: (1) identifying insects causing damage to forest resources (largely timber); (2) describing their biology and the damage they cause; and (3) developing methods for killing them. In the post-World War II era, forest entomology was revolutionized in part by the availability of very effective insecticides, which greatly facilitated task (3). Furthermore, the post-war availability of aircraft, along with highly effective pesticides, provided a combination that offered remarkable possibilities for killing large numbers of insects over vast areas.

Beginning in the 1960s and the 1970s, matters became more complicated. Societies awakened to the realization that the routine and widespread practice of spraying with insecticides could have undesirable effects both on human health and on the environment. There was also a realization in the scientific community that insects were not necessarily ''enemies'' and that many forest insects, even tree-killing bark beetles, provided useful services and played important roles in ecosystem dynamics. Furthermore, the entire field of forestry has undergone something of an upheaval. In most parts of the Americas, forest management activities had previously concentrated on the extraction of fibre from extant forests. But as the availability of these forests diminished and the demand for fibre increased, forestry has shifted toward management of either secondary forests or plantation forests. There has also been increasing emphasis on managing forests for non-market values, such as amenity (scenery, recreation) and wildlife (Bengston 1994).

With these shifts in social values and the re-orientation of forestry practices, the field of forest pest management has become more complex. Simply killing insects is no longer the primary objective and with the advent of integrated pest management, the field now also emphasizes surveillance, risk assessment, area-wide management, biological control and adaptive management. The other important driver of change in forest pest management has been the onset of globalization and the accompanying problem of biological invasions. Increasingly, species are being accidentally moved outside of their range into new regions where they often thrive and cause extensive damage (Liebhold et al. 1995; Aukema et al. 2011). Consequently, the focus of forest pest management is shifting toward the problem of minimizing invasions and their adverse effects.

Clearly, the world will not stand still, and forest pest management will need to adapt and change. Below, I outline a few important considerations for forest pest management in the future. Though it is never possible to predict the future with complete

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accuracy, considerable insight can be drawn from some of the recent trends in forest pest management.

2. It is a people problem

Even though many forests occur in relatively isolated areas and exhibit little superficial evidence of human activity, both the causes and consequences of most forest insect outbreaks can be traced back to humans (Jenkins 1997). Failure to address the social aspects of forest pest problems amounts to the neglect of a critical component of these problems.

Human constructs such as global trade, climate change, fire suppression and forest management have all been implicated as causes of forest insect problems. But equally important are the human aspects of the consequences of forest insect outbreaks. Consider the highly relevant but slightly overused philosophical question, ''If a tree falls in the forest and nobody hears it, did it really fall?'' From a perspective of forest pest management, the answer is surely ''no''. A problem is not really a problem unless a person says it is a problem.

All forest insect outbreaks are not inherently undesirable. Trees do not last forever and their death serves to make way for the next forest. There are many examples of insect ''damage'' playing an important and useful role in natural forest dynamics. Even tree-killing bark beetles, though cursed by many, play important role in forest nutrient cycling and other ecosystem processes (Griffin et al. 2011). Massive outbreaks of several defoliator species, such as the spruce budworm *Choristonura fumiferana* (Clemens), are known to have recurred over thousands of years and the mortality they cause is critical in the dynamics of boreal forests (Bouchard et al. 2006).

It is only when the adverse effects of insect outbreaks intersect unfavorably with resources valued by humans that such insects are considered to be pests. As such, it is important that forest pest management programmes connect with the real problem – people. In some cases this means limiting control efforts to forests that are highly valued, whether for timber that is about to be harvested, recreation or as a residence. For example, suppression of Gypsy Moth, *Lymantria dispar* (L.) outbreaks with aerial spraying of pesticides is typically limited to residential areas because those are where economic impacts are greatest (Leuschner et al. 1996). While this insect may have some deleterious effects on timber and other land uses, these impacts are generally minor and may not justify the expense of protection via aerial spraying.

In some cases, the perception of pest impacts may exceed reality. This can be a delicate matter if the public is clamouring for their government to protect the forests when, in the long run, it may be better to let nature take its course. For example, in many areas of western North America where thousands of vacation homes have been constructed in pine forests, there has been uproar concerning the killing of trees by the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, but in many cases, these homes may not be at risk or it is impractical to take any action to prevent future damage (MacKendrick and Parkins 2005). Often, in this type of situation, education can be of critical importance. Distribution of information about insect damage can often ameliorate many of the fears held by residents and visitors. Such educational efforts may often be a more effective approach to reducing insect problems than would direct suppression of the insect populations themselves (McCullough 1994).

3. You can't terminate a regional outbreak using pesticides

Despite vast efforts spanning generations of forest insect research, we still only have a partial understanding of the forces operating that govern most forest insect outbreaks. Nevertheless, there are several characteristics of outbreaks that provide some insight into what can be accomplished via direct suppression of populations.

One concept that is common to the dynamics of many insect outbreaks is the importance of delayed effects. For example, the numerical response by specialist predators and parasitoids is often such that host densities in one generation determine the level of mortality in the next, rather than the current, generation (delayed density-dependence). One of the consequences of this is that by the time insect populations reach outbreak levels, it may be too late to prevent any damage. In many cases, populations may crash irrespective of control levels, due, for example, to intrinsic density-dependent mechanisms and epizootics. In an even worse scenario, the application of pesticides to check population growth may interfere with the density-dependent mortality normally inflicted by natural enemies and actually prolong an outbreak. An example of this can be found in studies of Gypsy Moth populations where spraying of some stands with the bacterial pesticide *Bacillus thuringiensis* Berliner prevented the onset of a virus epizootic and actually prolonged the outbreak (Woods and Elkington 1988).

Another common feature of insect outbreaks is spatial synchrony (Peltonen et al. 2002; Liebhold et al. 2004). In most species, the densities of disjunctive populations of insects rise and fall together and this synchrony may extend over hundreds of kilometres. The causes of spatial synchrony in insect populations are often unclear, though it is known that it can arise via the effects of synchronous weather influences (the so-called ''Moran effect''), dispersal of individuals among populations, or dispersal of natural enemy populations. In any case, the existence of this synchrony may be of profound significance to management of outbreak populations, because suppression of populations at individual locations will not influence the inertia of outbreaks that extends over large regions. Liebhold et al. (1996) analysed regional data on Gypsy Moth populations following aerial suppression treatments that were applied when populations exceeded damage thresholds. They found that while most treatments prevented damage in the year of treatment, their effects became indiscernible in subsequent years, presumably because these populations once again became entrained in the dynamics of the regional outbreak.

In summary, a realistic objective of most population suppression should be short-term local protection, rather than long-term termination of regional outbreaks.

4. Silvicultural control – a good idea, but with some reservations

As mentioned above, many forest insect outbreaks can be traced to human actvities. Past forest management practices are a prime example. Failure to control wildfires may predispose Central American pine forests to outbreaks of tree-killing *Dendroctonus* spp. (Billings et al. 2004). Conversely, fire suppression may result in changes in forest composition that increase susceptibility to forest insect outbreaks (McCullough et al. 1998), as is the case with the Western Spruce Budworm, *Choristoneura occidentalis* Freeman, in western North America (Anderson et al. 1987). Similarly, the massive outbreak of the Mountain Pine Beetle, currently underway in western North America, is believed to be the combined result of historical cutting practices, fire suppression and climate change, which have promoted the development of large expansive stands that are highly prone to beetle attack (Raffa et al. 2008).

These situations, where current problems can be attributed to forest management practices, offer opportunities for reducing pest impacts via silviculture. Practices such as thinning and clear-cutting are not something that most people would consider to be "natural" activities, but in many cases the effects of these treatments may mimic natural disturbances such as fire which are critical in the maintenance of a particular combination of forest structure and composition that is resistant to insect impacts. As such, there has been considerable success in the use of silviculture as an effective long-term solution to insect problems. In particular, thinning has been used successfully to reduce stand susceptibility to several species of bark- and wood-boring insects; tree vigour is often a critical determinant of resistance to such insects, and reducing stand density may increase vigour and thereby reduce stand susceptibility (Fettig et al. 2006).

There are, however, caveats to the use of silviculture in forest pest management. First, there may be serious economic constraints upon the practicality of silvicultural approaches. In many systems intermediate harvests or thinning may be too expensive. In other situations, lack of road access or potentially adverse visual impacts may prohibit the thinning of forest stands. Another, and perhaps more important, limit on the application of silviculture is that the benefit from such practices may be minimal or non-existent. Unfortunately, there has sometimes been a lack of scientific rigour applied in the identification of silvicultural practices for reducing forest insect damage. In several systems, particularly those involving defoliators, silvicultural recommendations have been based upon extrapolation from correlations of stand characteristics with damage rather than based upon experimental manipulations (Kemp 1980; Muzika and Liebhold 2000).

In summary, silviculture can be an effective approach to managing forest pest problems in many systems, but definitely not all. Probably the best success stories in the use of silvicultural practices have been in the reduction of stand susceptibility to damage from bark- and wood-boring insects, which often exploit trees of low vigour. While improving stand vigour may protect trees from certain types of insect, it has no effect on populations of other species. In particular, many foliage-feeding insects may not be good candidates for silvicultural management.

Considerable recent work indicates that forest susceptibility to damage from insects is inversely related to forest tree diversity (Jactel and Brockerhov 2007). This would obviously suggest that practices promoting high tree diversity would be beneficial, but such generalizations might be dangerous. First, there is the disparity between correlation and causation. To date there is no *experimental* evidence that diverse forests are less prone to insect damage than monocultures; the hypothesis is generally based on correlative studies. Second, there may be logistical constraints upon the management of tree diversity; monocultures are often simpler to manage and may generate higher yields (Kelty 2006). The costs and benefits of forest tree diversity needs further study. Thus, the benefits of managing for forest diversity is not clear-cut and anticipated benefits from silvicultural manipulation of diversity are uncertain.

Instead of using silviculture to manage forests simply for diversity, there may be more value in broadening the goal to management for resilience, a term that refers to the capacity of an ecosystem to return to its previous state following perturbation (Holling 1973). Unfortunately, dissecting the components of resilience for any forest ecosystem can be a complex and difficult undertaking, and it obviously places a limit upon management for resilience. Climate change and biological invasions may greatly alter the conditions for resilience and so further complicate the problem (Thompson et al. 2009).

5. Better to deal with invasions sooner rather than later

In virtually every part of the world we are facing something of a crisis resulting from adverse impacts of non-indigenous forest insects and diseases. The problem of biological invasions can be traced to globalization: trends of increasing trade and travel have resulted in the accidental movement of herbivorous insects out of their native range. As a result of release from natural enemies, or exposure to novel hosts, many of these insect species have thrived in their new habitats and caused considerable damage. Most non-native insects never cause noticeable damage (Aukema et al. 2010), but several of these species cause damage that may exceed the impacts of native insects. For example, the Emerald Ash Borer, *Agrilus planipennis* Fairmaire, native to eastern Asia has invaded central North America and appears to be poised to extirpate the majority of North American ash trees, both in naturally regenerating forests and those planted in urban settings (Poland and McCullough 2006).

Extensive bioeconomic studies of invasions indicate that the expenditures to manage invasions are generally more efficient if they are applied as early on as possible in the invasion process (e.g. Leung et al. 2002; Saphores and Shogren 2005). All invasions proceed through the same three steps: arrival (transport to the exotic habitat), establishment (growth of the newly founded population to a point where extinction is no longer likely) and spread (expansion of the species range into the suitable exotic habitat). A relatively modest expenditure made to prevent an invasion can be extremely beneficial, because it may preclude an eternity of otherwise irreversible expenses arising from both pest impacts and management following widespread establishment.

The most effective starting point is to prevent arrival. We know that most forest insects arrive via accidental transport either with wood or live plants (Haack 2001; Liebhold et al. 2012). Progress has been made in closing these invasion pathways; for example, the enactment of ISPM-15 by the International Plant Protection Organization, being an international quarantine on the movement of solid wood-packing material, should greatly reduce the arrival of wood-boring insects (Haack and Petrice 2009). However, many enacted quarantines may not be effective and other pathways remain essentially wide open. Closing these routes is complex and difficult because quarantines may adversely affect trade and have negative economic impacts. As such, it is not realistic to expect that all invasion pathways can ever be closed. Furthermore, trends of increasing trade and travel can be expected to increase propagule pressure (Levine and D'Antonio 2003), thereby increasing rates of establishment of non-native species in the future.

Since arrival cannot be stopped, the next best approach is to prevent establishment. This can be accomplished via early detection of new colonies of potential pests, when eradication is still possible. New Zealand currently has perhaps the world's most comprehensive exotic forest pest surveillance system (Bulman 2008), and other countries would be well advised to follow its lead. The system employs networks of attractant traps for detecting exotic pests that have been previously identified as potentially damaging. It also employs aerial surveys and random vegetation sampling for detection of newly-arrived forest insects and pathogens. While not perfect, such surveillance systems are of critical importance for exclusion of damaging species and are a cost-effective approach for preventing extensive damage that would occur from widespread establishment.

When invading species are discovered early and are not widely distributed, eradication is of critical value in the prevention of future pest impacts (Sharov and Liebhold 1998). The science behind insect eradication is still relatively young, but theoretical and empirical evidence indicates that many invading insect populations exhibit Allee effects (decreasing population growth rate with decreasing density) and this may facilitate eradication. Allee effects can create population thresholds, below which populations proceed toward extinction without intervention; eradication can thus be achieved by suppressing populations below these thresholds; thus, it is therefore not necessary to kill every individual in order to cause a local population to become extinct (Liebhold and Tobin 2008; Tobin et al. 2011). Methods such as mating disruption, sterile insect releases and mass-trapping intensify intrinsic Allee effects and may thus be particularly useful strategies for eradicating small, newly founded populations.

6. Planting exotic trees is a risky business

As the world's population grows and the demand for wood fibre increases, an increasing fraction of global demand for wood products derives from plantations of non-native trees (Sedjo 2001). Particularly in the southern hemisphere, exotic tree species such as *Pinus* and *Eucalyptus* provide much higher yields of high-quality fibre compared with native species.

Though rarely acknowledged, much of the high productivity in plantations of non-native tree species can be attributed to their escape from disease and herbivory by pathogens and insects that they face in their native range. As a result, growth rates of many of these widely planted species are typically much higher than in their native range. A good example of this is provided by *Pinus radiata*. In its native range in North America, trees are small, are poorly formed, and are slow-growing, but in exotic plantations in New Zealand, Chile and Australia, they exhibit remarkable growth and are widely utilized for fibre production. At least some of this difference can be explained by the greater abundance and diversity of herbivorous insects in native stands compared with exotic plantations (Ohmart and Voigt 1981; Britton and New 2004).

Unfortunately, the remarkable productivity of exotic tree plantations generally cannot continue indefinitely. It can be expected that pathogens and herbivorous insects will eventually "catch-up" with their host trees, in terms of overcoming the plants' defences. This phenomenon can be seen happening now, around the world. Pines are not native to the southern hemisphere where they have been widely planted, and they exhibit remarkable productivity. However, one pine herbivore, *Sirex noctilio* F., has colonized virtually every major-pine producing region in the southern hemisphere, where it has often become a major pest that threatens plantation forestry (Carnegie et al. 2006). The insect is native across temperate Eurasia and typically causes little damage, but in exotic pine plantations, where no other bark- or wood-borers typically exist, this insect thrives, sometimes exhibiting massive outbreaks that cause the death of thousands of trees. Another example of insect species "catching-up" with their widely planted hosts outside of their range is provided by the insect herbivore guild associated with *Eucalyptus* species. In their native ranges in Australia, these trees species support a diverse fauna of herbivorous insects, but in the extensive plantations of these trees elsewhere in the world, insects are much less abundant and trees exhibit remarkable growth (Ohmart and Edwards 1991). However over the last 20 years, several insect herbivore species have colonized exotic *Eucalptus* plantations and caused extensive damage (Withers 2001; Wingfield et al. 2008). This trend can be expected to continue and represents a significant threat to the dependence on *Eucalyptus* as a source of fuel and fibre in many developing countries.

Plantation forestry utilizing non-native tree species has proven to be a highly productive endeavour, and this industry is providing an increasingly large fraction of the world's fibre and fuel. Given the importance of the escape of exotic trees from their native community of insect herbivores, it is critical that invasions by these species are prevented. The failure of quarantine, pest surveillance and eradication programmes to exclude these insect species results in the accumulation of potentially damaging pest species that hold the potential to decimate such forest industries. Consequently, it is essential that countries that depend on exotic tree plantations should invest considerable resources into quarantine, inspection, surveillance and eradication in order to protect their forest industries. Exotic tree plantations are often widely utilized in countries with developing economies and such countries may not have the resources to invest in biosecurity programmes. In such cases, it may be advisable that dependence on exotic trees as a source of fuel and fibre be minimized; native species may ultimately represent more dependable resources for forestry.

7. Classical biological control and tree resistance breeding are worthy endeavors

Release from natural enemies is one of the main reasons for the extreme success of certain non-native species. Probably the best evidence for the natural enemy release hypothesis comes from the ample examples of invading forest insect species that historically ceased their outbreak population behaviour following the introduction of natural enemy species. A good example is provided by the winter moth, *Operophtera brumata* (L.), which declined to sub-outbreak levels following introduction of parasitoid species into invading populations in Nova Scotia and British Columbia (Roland and Embree 1995).

Classical biological control (the importation and establishment of natural enemies from a pest's native range) has been used for over a century as an approach to reducing the damage caused by non-native pests. In recent years, there has been recognition of potentially adverse affects of imported natural enemies on "non-target" native species. One of the best-documented cases of this is the apparent widespread decline of several North American saturniid moth species as a likely result of the introduction of the tachinid, *Compsilura concinnata* (Meigen), for control of the Gypsy Moth (Boettner et al. 2000). However, such negative impacts can only occur from the introduction of generalist natural enemies, and modern approaches to biological control include screening of potential hosts to avoid introduction of species with wide host ranges (Jervis and Kidd 2005). Thus, if classical biological control is followed using widely accepted procedures, it should be a powerful and safe approach to minimizing the impacts of invading pest populations.

The other principal hypothesis for explaining the excessive population growth of non-native herbivore species posits that plants co-evolve with herbivorous insects (Rausher 2001) and thereby develop physiological mechanisms for either deterring the attack of insects or tolerating their feeding. When insects invade new regions and encounter tree species with which they share no previous evolutionary history, they may be able to exploit hosts with little or no defence. An example of this is seen in the hemlock woolly adelgid, *Adelges tsugae* (Annand), which does not reach damaging levels on native hosts, even when they are planted in its exotic range in eastern North America where the adelgid severely defoliates and kills Eastern Hemlock, *Tsuga canadensis* (L.) (Montgomery et al. 2009). Given such evidence of potential host resistance, there may be great benefit in searching for naturally occurring resistant genotypes within affected host species or investigating the propagation of exotic hosts or their hybrids.

8. Conclusions and future prospects

There is little doubt that the two strongest drivers of future environmental change are biological invasions and climate change. Much of the aforementioned discussion focuses on how forest pest management must adapt to the problem of biological invasions. Current globalization trends can be expected to continue and, as a result, non-native species can be anticipated to continue to invade new parts of the world and pose serious threats to forest resources.

In contrast, none of the advice given above focuses on the problem of climate change. There is little doubt that world's climate is changing and will likely alter at a more rapid rate in the future. There are ample examples of forest pest problems with causes rooted in climate change. For example, the current massive outbreak of the Mountain Pine Beetle currently underway in the Rocky Mountains is believed to have resulted in part from changes in temperature that have created favourable conditions for beetle development in regions where the insect could previously not reproduce so well (Logan et al. 2003). In other areas, shifts in climate have caused trees to be poorly adapted to local conditions, resulting in lowered resistance to tree-killing bark beetles, and so massive outbreaks have resulted (Breshears et al. 2005). The latter phenomenon is something that can be anticipated, given that tree species ranges are likely to shift in coming decades (Hansen et al. 2001): as the regions climatically optimal for given tree species shift to higher elevations and latitudes, large extents of forests will be comprised of species poorly suited for local environmental conditions and the abundance of such stressed trees can be expected to trigger outbreaks of tree-killing insects.

Despite the considerable evidence that climate change will alter pest outbreak dynamics, it is difficult to generalize about the overall consequences. Although there are examples, such as those mentioned above, of damaging pest outbreaks triggered by climate change, there are also examples of outbreaks that have been diminished by climate change (Ims et al. 2008). One particularly stark example of this is provided by the Larch Budmoth, *Zieraphera diniana* (Guenée), which is known to have periodically reached outbreak levels for over 1200 years, but over the last two decades these recurrent outbreaks have largely stopped, apparently as the result of unprecedented climatic warming (Johnson et al. 2010). Given the unpredictability of future climate change on insect outbreak dynamics, there is currently little useful advice on the direction that forest pest management should take in the future in anticipation of climate change.

Uncertainty associated with the effects of climate change on pest outbreak dynamics is just one of the problems facing pest managers. Future demand for forest resources such as wood and pulp also is uncertain. Tremendous opportunities exist for the utilization of forests as a source of biofuels, and it is possible that that demands for forest biofuels will shape the composition of future forests as well as determining which insects will be forest pests. Unknown social changes could additionally alter the nature of forest pest management. Growing public concern about human impacts on forests may play an increasingly important role in identifying the need for and approaches toward forest pest management in the future.

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