XANTARES BIOCIENTÍFICOS

Dende o grupo de traballo de formación e divulgación de **BioReDes** queremos anunciar a segunda charla encadrada nos ***Xantares Biocientíficos***, que terá lugar o **venres 3 de maio ás 13:00 horas no edificio CACTUS**. A intervención levará por título **"A sanidade forestal no contexto da globalización**" e será impartida pola **Dra. María Josefa Lombardero Díaz**, Investigadora do Departamento de Produción Vexetal da Escola Politécnica e da Unidade de Xestión Forestal Sostible (UXFS) da Universidade de Santiago de Compostela. Para que poidades ter información de antemán sobre a importancia do tema, achegámosvos dous artigos científicos e un breve resumo da presentación.

Aproveitamos para lembrar que, se tedes suxestións sobre charlas de interese para os ***Xantares Biocientíficos***, podedes remitilas a Iago Rodríguez, técnico de I+D da Agrupación (iago.palmeiro@usc.es)

Esperámoste! Ven a tomar un petisco con BioReDes!

<u>Breve resumo da presentación</u>

"A sanidade forestal no contexto da globalización"

María Josefa Lombardero Díaz.

Investigadora do Departamento de Produción Vexetal da Escola Politécnica e da Unidade de Xestión Forestal Sostible (UXFS) da Universidade de Santiago de Compostela.

O sector forestal galego xoga un papel fundamental na economía galega e española xa que Galicia produce practicamente a metade da madeira de España. Pero ademais destes beneficios económicos os montes galegos prestan tamén servicios ecosistémicos e sociais de gran importancia para moitos sectores da poboación.

Sen embargo nos últimos anos propietarios, xestores e investigadores estanse enfrontando a uns desafíos sen precedentes no ámbito da sanidade forestal debido o rápido incremento de pragas e enfermidades que comprometen o bo funcionamento dos montes e cas que non teñen experiencia previa. Moitas destas pragas e enfermidades son introducidas, pero outras son especies nativas que empezan a comportarse como pragas aínda que antes non o eran. As causas fundamentais deste problema radican en tres pilares que analizaremos polo miúdo: os cambios que se están a producir no clima, no uso da terra e na distribución global de organismos.

NRC Research Press

CONCEPT PAPER

Forest pests and their management in the Anthropocene[1]

Matthew P. Ayres and María J. Lombardero

Abstract: Forest managers are facing unprecedented challenges from rapid changes in forest pests. The core causes are changes in climate, land use, and global distributions of organisms. Due to invasions and range expansions by pests, and propagation of nonnative trees, managers are increasingly confronted with pest problems outside their range of experience. There is a need to adapt pest management practices more quickly and efficiently than is possible when managers work in isolation and mainly learn by trial and error. Here we identify general tactics for adaptation of forest pest management in the Anthropocene: growth and application of practical theory; improved biosecurity against future invasions; improved monitoring, prediction, and mitigation; increased sharing of knowledge among regions, countries, and continents; management plans that anticipate continuing change; improved assessment of costs, benefits, and risks of possible responses to new potential pests; assessment of system responses to pest management decisions so that subsequent decisions are increasingly better informed; and improved understanding of the couplings between forests, forest management, and socioeconomic systems. Examples of success in forest management can aid in other sectors (e.g., agriculture, pastoralism, fisheries, and water resources) that are similarly important to our environmental security and similarly challenged by global change.

Key words: adaptive management, Anthropocene, climate change, forest pests, forest management.

Résumé : Les aménagistes forestiers font face à des défis sans précédent à cause des changements rapides chez les ravageurs forestiers. Les principales causes sont les changements climatiques, l'utilisation des terres et la distribution mondiale des organismes. À cause de l'invasion et de l'expansion de l'aire de répartition des ravageurs ainsi que de la propagation des espèces d'arbres exotiques, les gestionnaires sont de plus en plus confrontés à des problèmes phytosanitaires auxquels ils ne sont pas habitués. On doit adapter les pratiques de gestion des ravageurs plus rapidement et efficacement qu'il est possible de le faire lorsque les gestionnaires travaillent encore en vase clos et apprennent surtout par essais et erreurs. Dans cet article, nous identifions des tactiques générales pour adapter la gestion des ravageurs forestiers dans à l'ère de l'anthropocène : croissance et application de la théorie applicable; meilleure biosécurité face aux invasions futures; amélioration du suivi, des prévisions et des mesures d'atténuation; augmentation du partage des connaissances entre les régions, les pays et les continents; plans d'aménagement qui anticipent le changement continu; meilleure évaluation des coûts, des bénéfices et des risques des réactions possibles face aux nouveaux ravageurs potentiels; évaluation des réactions du système aux décisions de gestion des ravageurs de telle sorte que les décisions ultérieures soient de mieux en mieux éclairées; et meilleure compréhension des relations entre les forêts, l'aménagement forestier et les systèmes socioéconomiques. Les exemples de succès en aménagement forestier peuvent être utiles dans d'autres secteurs (p. ex., l'agriculture, le pastoralisme, les pêches et les ressources hydriques) qui sont aussi importants pour notre sécurité environnementale et également remis en question par le changement à l'échelle du globe. [Traduit par la Rédaction]

Mots-clés : aménagement adaptatif, anthropocène, ravageurs forestiers, aménagement forestier.

Introduction

There is growing agreement that recent dramatic changes to Planet Earth from globalization and related human activities meet the standards for recognizing a new geological epoch (Waters et al. 2016). It can be said that the Holocene is over and we now live in the Anthropocene. The three prominent features of contemporary anthropogenic global change (Millennium Ecosystem Assessment 2005) all have broad and general consequences for forests and forest management (Seppälä et al. 2009; Liebhold 2012; Millar and Stephenson 2015; Trumbore et al. 2015): (1) concentrations of atmospheric CO_2 that are unprecedented for at least 800 000 years are changing climate, disturbance regimes, and the pools and fluxes of energy and matter in forest ecosystems; (2) increasingly intensive human land use is changing the extent and nature of forests, for example increasing the proportion of forested land that is actively managed; and (3) the tree species that make up forested land and the pests and pathogens that afflict them are being dramatically altered by deliberate propagation of nonnative tree species and by introductions and range expansions of pests, pathogens, and weeds. Thus, even as forests become increasingly important to human welfare (FAO 2016), they are increasingly challenged by pests and pest management problems that are outside the range of experience of shareholders and caretakers (Liebhold 2012). It appears that managing pests will be an even greater challenge for forest management in the Anthropocene than it ever has been (Malhi et al. 2014; Millar and

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Stephenson 2015). Recognizing the shared causes for new challenges in forest pest management can suggest some general tactics for human adaptation. Here we attempt to identify strategies for forest pest management in the Anthropocene that match the global nature of the problem (Trumbore et al. 2015).

Range expansions and human-aided intercontinental invasions by forest pests and pathogens are generating significant new problems for forests and forest management in ecosystems around the world. For example, climate warming has permitted at least three species of highly aggressive tree-killing *Dendroctonus* bark beetles to expand their ranges within North America into conifer forests at higher latitudes and higher elevations than just a few decades ago — with broad consequences for ecosystems and people (Bentz et al. 2010; Weed et al. 2013). Similarly, warming temperatures have permitted poleward expansions of native defoliating caterpillars (Geometridae) in Fennoscandia that are changing mountain birch ecosystems and threatening the environmental security of Sami reindeer herders (Jepsen et al. 2013). Further, one of the most damaging forest insects in the Mediterranean region, the pine processionary moth, is extending its range north into European pine forests that have previously been protected by temperatures too cold for the winter-feeding larvae (Battisti et al. 2005).

Notable intercontinental invasions of pests and pathogens are already in the hundreds and growing rapidly (Klapwijk et al. 2016; Liebhold et al. 2016*a*; Lovett et al. 2016; Roques et al. 2016). Examples include the incipient elimination of native ash from North America by the invasion from Asia of emerald ash borer (Herms and McCullough 2014; IUCN 2017); establishment of pine wilt disease in Portugal caused by an invasive nematode from North America that is vectored by native *Monochamus* beetles (Mota et al. 1999; Vicente et al. 2012); chestnut blight, introduced from Asia, which virtually extirpated chestnuts from North America and is now threatening chestnuts in Mediterranean Europe (Dutech et al. 2012); and the chestnut gall wasp *Dryocosmus kuriphylus* also from Asia (Brussino et al. 2002; Graziosi and Santi 2008), which is increasing the frustration of chestnut producers in Europe and contributing to the abandonment of chestnut forests that have been a source of nuts, wood, and cultural context for millennia. Pitch canker disease (*Fusarium circinatum*) (Wingfield et al. 2008), Diplodia blight (Wingfield et al. 2001), and Dothistroma needle blight (Bulman et al. 2016) have become globally important fungal pathogens of pines, and many species of *Phytophthora* (Oomycota) are causing unprecedented damage to crops, landscape plants, forests, and other ecosystem types around the world (e.g., *Phytophthora cinnamomi* in southern Europe and Australia and *Phytophthora ramorum* in North America and Europe) (Derevnina et al. 2016). There are also growing examples of novel pathogens whose emergence seems associated with invasions, e.g., a genetic change in the invasive fungus *Ophiostoma ulmi* (now *Ophiostoma novo-ulmi*) has enabled the killing of European elms that survived the first pandemic of Dutch elm disease (Brasier 1991) and hybridization between species has apparently amplified virulence within the species complex *Phytophthora alni senso lato*) (Husson et al. 2015), which is now threatening riparian and freshwater ecosystems of western Europe by eliminating alder wherever it has thus far reached (Bjelke et al. 2016).

Pestilence in novel ecosystems is another broad category of emerging challenges for forest management in the Anthropocene (Wingfield et al. 2015). As a feature of both land use changes and alterations to biota in the Anthropocene, there are now millions of hectares of production forests around the world that involve propagation of monocultures of nonnative tree species (FAO 2010). Dramatic examples include pine plantations in the Southern Hemisphere and Eucalyptus plantations outside Australia. One motivation for using nonnative tree species for production forests is that the trees are removed from their natural herbivores and pathogens (enemy release hypothesis, within T-10 in Fig. 1). However, enemy release can also work to the benefit of nonnative herbivores when they arrive (Elton 1958), and we now know that nonnative trees can be highly susceptible to accidental introductions of plant-eating organisms in novel ecosystems (Liebhold 2012). For example, *Sirex* woodwasps, which are native to Europe where they are not a pest (Lombardero et al. 2016), have become an enormous pest of pine plantations in the Southern Hemisphere following their accidental introduction via wooden shipping materials (Slippers et al. 2012). Also, invasive *Gonipterus* beetles, native to Australia, are challenging the viability of Eucalyptus production forests in China, Africa, South America, Europe, and North America — that is, on every continent where nonnative Eucalyptus is being grown (Reis et al. 2012).

Eight general tactics for improved pest management in the Anthropocene

Here we identify and describe eight general tactics for improved pest management in the Anthropocene. Throughout, we emphasize the value of ecological theory in understanding, anticipating, and adapting to the rapidly changing world of forest–pest interactions. We posit that reference to theory promotes effective communication and cooperation among forest shareholders, managers, and scientists. Our aim is to promote strategic responses to a package of challenges (see Introduction) that are shared by the many sectors, players, and people who interact with forests globally. Each section includes consideration of current barriers to application of the tactic and possible pathways to more successful application.

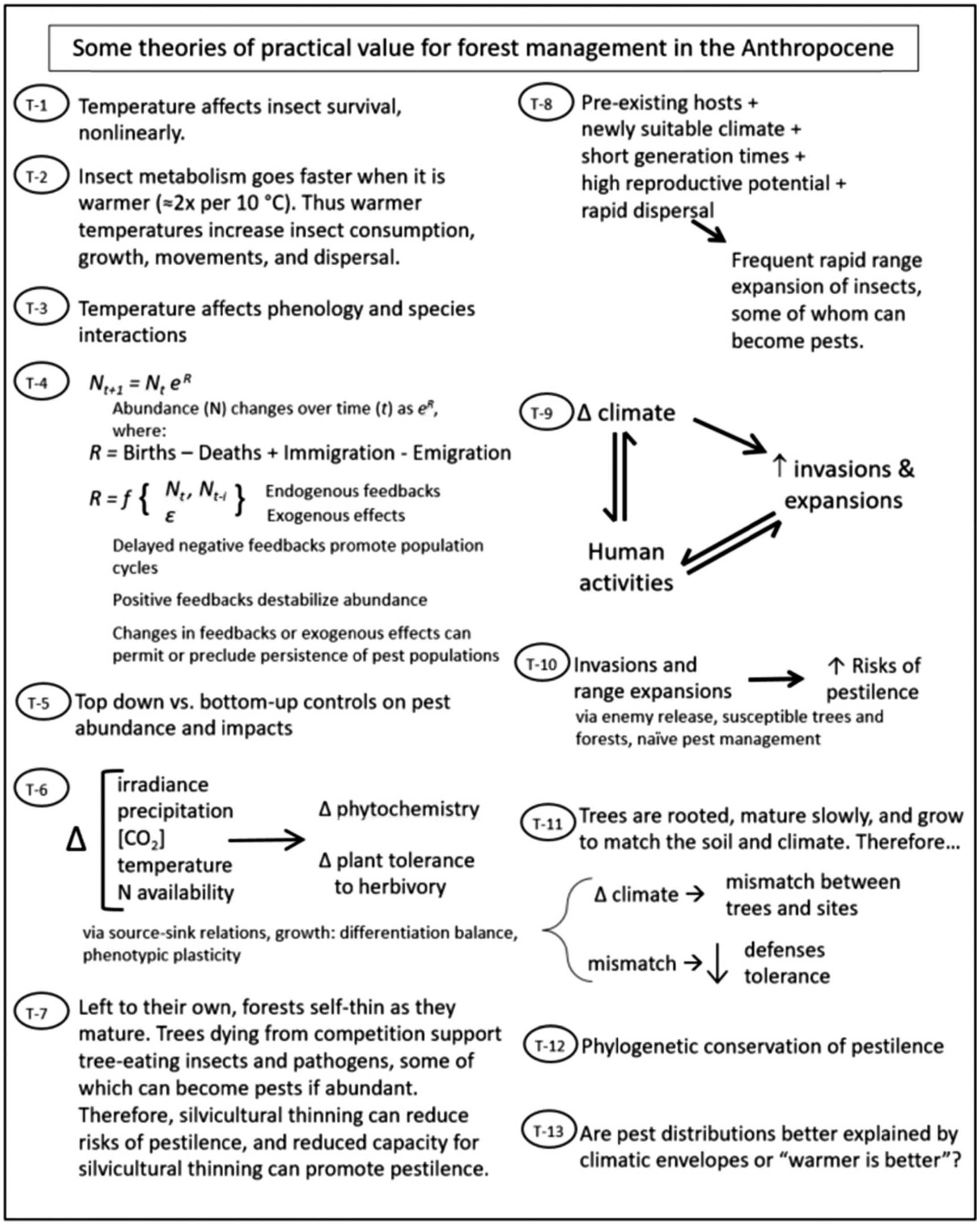
1. Growth of practical theory that is transportable among forests and regions

There is nothing more practical than good theory. Good theory allows for more rapid progress than accumulating experience by trial and error and for more reliable extrapolation of management practices from one region or forest type to another and from one pest to another. Figure 1 summarizes a subset of the theories that are clearly relevant to forest pest management in a changing world. Our examples have been chosen to illustrate some broad categories of practical knowledge that lie at the intersection of science and management: effects of temperature on pests (T-1–T-3); determination of pest abundance (T-4 and T-5); environmental effects on plant defenses and tolerance to herbivory (T-6); silviculture and forest pests (T-7); causes of range expansions in potential pests (T-8 and T-9); consequences of range expansions (T-10 and T-11); evolutionary tendencies of insect species to be pests and tree species to suffer from pests (T-12); and effects of climate change on the geographic distribution of potential pests (T-13).

A theory as used here is a syllogism — a set of propositions (postulates), each of which might or might not be true, but which when put together lead logically to generalizations broader than any of the component postulates (Lewis 1994; Pickett et al. 2007; Scheiner and Willig 2011; Vellend 2016). Within Fig. 1, this structure is most explicit in T-7, T-8, and T-11. Other examples are more briefly represented in Fig. 1 by an emergent generalization from the theory that is relevant to forest pest management: T-1–4, T-6, T-9, T-10, and T-12. Two examples portray pairs of theories that are in competition with each other (T-5 and T-13), with the resolutions having consequences for forest pest management.

Our examples of theories are diverse in terms of maturity (Loehle 1987). At one extreme, we know beyond reasonable doubt that insects have upper and lower thermal thresholds for survival (T-1) (Bale et al. 2002), that insect metabolic rate increases approximately exponentially with temperature ($Q_{10} \approx 2$) (T-2) (Gillooly et al. 2001), that biological populations change as a function of *e* (the base of the natural log), and that the dynamics of populations are governed by density-dependent feedback systems with modification by environmental factors that vary independently of density (T-4) (Berryman 2003; Klapwijk et al. 2012). The relative

Fig. 1. Thirteen theories or sets of theories that are of general practical value for anticipating and managing changes in forest pestilence in the Anthropocene. See text for further elaboration.



importance of top-down versus bottom-up controls on herbivory (T-5) has been the subject of thousands of studies over decades (Hairston et al. 1960); this has shown that nature includes the full continuum of possibilities but has also yielded increased capacity to predict which possibility will more likely be true in system *X* within environment *Y* (Hunter and Price 1992). Similarly, increasingly sophisticated understanding of source–sink relations in plant carbohydrates and environmental effects on plant defenses allows informed hypotheses and defensible generalizations regarding phenotypic patterns in phytochemistry and plant susceptibility to herbivory (T-6) (Herms and Mattson 1992; Lombardero et al. 2000; Hartmann and Trumbore 2016). Our understanding of climatic effects on the phenology of interacting species (T-3) is at intermediate maturity; we know that interannual variation in weather has strong effects on phenology that can vary among species (Parmesan 2006), and we are beginning to understand interspecific patterns in physiological controls on phenology (Pau et al. 2011; Valtonen et al. 2011; Buckley and Kingsolver 2012). As examples of theories that are presently immature but relevant to pest management, it is logical but has barely been tested that changing climate leads to physiological mismatch in trees because they grow to match the climate, which can change during their lifetime (T-11) (Zadworny et al. 2016). And we are only beginning to understand when, where, and how often warming temperatures will reduce the occurrence of potential pests in regions that were already relatively warm (climatic envelope hypothesis) versus simply relaxing constraints on poleward populations without concomitant reductions towards the equator (warmer is better) (T-13) (Gaston 2009; Angilletta et al. 2010; Currano et al. 2010).

Each of the theories or theory sets in Fig. 1 has practical value for forest pest management in the Anthropocene. For example, T-1–T-3 suggest the form for process-based models that can anticipate responses of insect distributions to changing climates. Theory from population ecology (T-4) can be applied to predict effects of resource quantity and quality on equilibrium pest abundance; the form and intensity of predation necessary for a successful biological control program; the extinction threshold that must be reached for a successful pest eradication program; the escape threshold above which bark beetle populations tend to erupt into epidemics; and the potential for unintentionally prolonging outbreaks by suppressing rising populations of pests with naturally cyclical dynamics. Insect species subject to strong top-down control in their native ecosystems are promising candidates for biological control of invasive populations, while those whose abundance is more a function of resource quality and quantity are not (T-5). From the theory set represented by T-6, it can be predicted that high availability of nutrients and water to trees will tend to reduce constitutive plant defenses but may increase the efficacy of inducible defenses and promote plant tolerance to herbivory. T-11 describes one way in which trees in particular are susceptible to rapid environmental change. T-9 describes a global feedback system that seems likely to drive continuing changes in climate and continuing invasions and range expansions by potential plant pests. T-8 identifies the features that promote range expansions by herbivores and T-10 identifies attributes that make invasions and range expansions more or less likely to result in new pestilence; together, these permit predictions of which insect species deserve the most careful attention by forest management. T-12 permits predictions of which insect species could be particularly damaging if they were to be accidentally introduced elsewhere and which tree species would be most vulnerable to an invasion by new insect species *X*. Resolving the question posed by T-13 can predict how often and where there will be reductions of pest impacts due to climate change. When T-7 applies, there is increased rationale for active management by silvicultural thinning.

The growth and maturation of practical theory will be aided if scientists can become better at studying research questions that matter to managers and become more adept at explaining the practical value of new knowledge to nonscientists (Cadotte et al. 2017). It would also be helpful if managers embrace scientific theories as tools of practical value. There is value in research when it can clarify the validity and generality of potentially relevant theories — especially when there are competing theories that have different consequences for management. There are opportunities for improved management when relevant theories are mature but not necessarily applied in practice. In the Anthropocene, it is more important than ever that scientists and managers cooperate and communicate. Clear and practical theories are a vehicle for doing so.

2. Improved biosecurity against future human-aided invasions

There is an urgent need to limit the role of humans in facilitating range expansions of potential pests. Forests all over the world are being negatively impacted by human-aided invasions of insects and pathogens from other continents and biogeographic regions (Aukema et al. 2010; Klapwijk et al. 2016; Roques et al. 2016). We should not be surprised when some invasions and range expansions by plant-eating organisms lead to pest outbreaks and tree mortality because newly occupied forests will commonly be more susceptible due to enemy release, susceptible trees and forests, and naïve pest management (T-10). Some invasives produce dramatic impacts such as the virtual extinction of some tree species (Herms and McCullough 2014). Frequently, as with the emerald ash borer in North America, there is little that can be done to limit damage once a new pest population has become established. The ideal strategy is to prevent new invasions. Most introductions are an accidental result of international transport of goods (Hulme 2009). Global trade is certain to continue increasing in the Anthropocene (T-9) (Roques et al. 2016). The future of forest health depends upon stemming the tide of invasions by tree-feeding organisms even with the inexorable growth of international trade. This is more tractable than it might seem because there are just a few main pathways for introductions: live plants, logs, and solid wood packing material (IUFRO 2011; Liebhold et al. 2012; Lovett et al. 2016). There are sensible and seemingly practical means of greatly reducing the introduction of new plant pests via these pathways (e.g., Eschen et al. 2015; Lovett et al. 2016). Implementing these actions will require new national laws and new international agreements as well as increased capacity for enforcement of laws and agreements (Roy et al. 2014). It seems that voters and lawmakers would support strong actions because, as it is, the enormous costs of invasive forest pests tend to fall on private citizens and municipal governments who lack the means to pay (Lovett et al. 2016). One pathway to limiting invasions is increasing public awareness of the problem and the solutions (Marzano et al. 2015; Klapwijk et al. 2016). New Zealand, which is a global model for limiting biological invasions, has exceptional biosecurity partly because of strong national will to do so, which is itself a product of high awareness by citizens of the socioeconomic costs of invasives (Goldson et al. 2015). There has been much progress in the theory and practice of managing biosecurity (FAO 2017), but much more is needed because the scale of propagule pressure from potential pests is presently overwhelming and still accelerating.

We can reduce but not eliminate introductions of potential new pests so there is also a need for expansion and improvement of pest monitoring programs to permit early detection (Liebhold 2012; Trumbore et al. 2015). Early detection, after introductions but before widespread establishment, can identify high-risk pathways and products that are likely to bring more of the same unless there are adaptive adjustments of shipping and trade practices. Also, there can be a window of opportunity for eradication while populations remain small and localized (Liebhold et al. 2016*b*). It is helpful that some of the most dangerous potential pests can be strategically targeted in prevention and detection programs because they are within clades (evolutionary groups of related species) with a propensity for killing trees due to the tissues they feed on, their proclivity for carrying microbial symbionts that can be phytopathogens, and (or) their tendency for outbreak population dynamics (phylogenetic conservation of pestilence (T-12)). Of the million plus species on Planet Earth, a tiny fraction account for the vast majority of plant pestilence, and many of those are evolutionarily related to each other (FAO 2005, 2007; Weed et al. 2013; European and Mediterranean Plant Protection Organization 2017*a*). Some examples include the following genera: *Agrilus*, *Dendroctonus*, *Ips*, *Hylastes*, *Pissodes*, and *Scolytus* (Coleoptera); *Choristoneura*, *Lymantria*, *Malacosoma*, *Operophtera*, and *Thaumetopoea* (Lepidoptera); *Adelges* and *Matsucoccus* (Hemiptera); *Armillaria* and *Fusarium* (Fungi: Ascomycetes); and *Phytophthora* (Oomycetes). Some of these clades have already contributed to the flood of forest pest invasions in recent decades and all are candidates to produce the next high-impact invasion if member species are introduced and established outside of where they already occur. The tendency for phylogenetic conservation of host use by plant-eating organisms can be a further aid in strategic prevention programs. For example, ports of entry with diploxylon pines in the area are especially vulnerable to introductions of potential pests that feed on hard pines. Sentinel tree nurseries can be used as a tool for identifying potentially dangerous pests before they have been accidentally introduced to a region with vulnerable tree species (Roques et al. 2015). In the Anthropocene, programs to prevent new pest introductions should take into account that ports of entry that were previously too cold for pest *X* may now be climatically suitable (T-9) (Weed et al. 2013).

3. Improved monitoring, prediction, and mitigation of established pests

Monitoring, prediction, and suppression of pests are time-honored tools of forest management and will be even more important in the Anthropocene due to changing patterns in the geography and species composition of pests and trees. We should expect increasing cases of rapid range expansions of tree-feeding insects due to preexisting hosts, newly suitable climate, short generation times, high reproductive potential, and high dispersal capacity (T-8) (Ayres and Lombardero 2000). Process-based models of population dynamics (T-4) can be combined with abundance estimates from monitoring programs to yield short-term predictions of abundance (and therefore risk of forest damage) that can be used to judiciously prepare for and implement suppression programs (Venette et al. 2010). Many detection and suppression programs can be improved with refinement of models to predict the seasonal timing of various insect life stages, which are changing and will continue to change due to the sensitivity of insect phenology to temperature (T–3) (Tonnang et al. 2017). Some positive examples of successful mitigation include development of chestnut root stocks resistant to Phytophthora (Pereira-Lorenzo et al. 2010) and biological control of *Gonipterus platensis*, a highly invasive defoliator of Eucalyptus, with a wasp from Australia that is an egg parasitoid (Reis et al. 2012).

4. Increased sharing of knowledge among regions, countries, and continents

Due to the tendency for particular groups of species to be pests (T-12, tactic 2), we can expect many cases of old pests in new places due to range expansions and human-aided invasions. This can help forest managers and shareholders who are experiencing new pests because there is usually practical knowledge of their biology and management from places where they have been historical pests. A problem is that under the status quo, transfer of knowledge among regions is frequently limited by institutional barriers and administrative boundaries. For example, there are rules, regulations, and customs within the US Forest Service that restrict their scientists and forest health professionals from traveling across boundaries between administrative regions — boundaries that are freely ignored by forest pests. Transfer of knowledge across international borders is also constrained, in this case because funding for forest health is local, provincial, or national, and there are no institutions that we know of with the mission and capacity to foster research and development that addresses the international dimension of forest health challenges. In our judgement, barriers to knowledge sharing within countries could be largely eliminated with little cost if they were addressed with flexibility and creativity by the cognizant administrators. But what are the pathways to more effective international cooperation in pest management? The European Union has recently enacted Regulation 1143/2014 on Invasive Alien Species ((European Commission 2017), which could be a model for elsewhere. Some other promising platforms that could support international efforts — if they were funded and encouraged to do so — include the Centre for Agriculture and Biosciences International (CABI), the International Plant Protection Convention (IPCC), the Commission on Phytosanitary Measures (CPM) within the Food and Agriculture Organization of the United Nations (FAO), the Standards Committee (SC) within ICPM, and the Sanitary and Phytosanitary Measures Committee (SPS) within the World Trade Organization (WTO) (European and Mediterranean Plant Protection Organization 2017*b*). The International Union of Forest Research Organizations (IUFRO) is well suited for providing relevant scientific input with a global perspective.

5. Beyond catastrophism

The job of forest scientists and managers who work with pests is to focus on the pestilence. However, pests are not becoming worse everyplace. For example, southern pine beetle (SPB) in its traditional range has become less of a pest than any time in many decades (Clarke et al. 2016). This is at least partly because of the success of detection, suppression, and prevention programs (Nowak et al. 2015). Furthermore, it must be that climate change is producing weather that is less suitable than before for some pests in some places (e.g., the warm parts of historical distributions when the physiological model of climatic envelopes applies (T–13). It would be helpful if it were someone's job to identify places where forest pests are becoming less severe because taking advantage of these situations where they occur is a part of adaptive responses by humans to a changing world (Seppälä et al. 2009 and tactic 8).

6. Improved assessment of costs, benefits, and risks

There is an urgent need for improved capacity to respond strategically to newly emerging plant pests. In 1989, the pine shoot beetle (*Tomicus piniperda*), which is a forest pest of moderate importance in its native Europe, was discovered in the Great Lakes states of the United States (Haack et al. 1997). This was one of the first of contemporary forest pest invasions in North America that raised the specter of catastrophic impacts. It was not generally appreciated that this was going to be the first of many more. At the time, it seemed logical to take the strongest possible actions to prevent this insect from reaching the extensive and highly productive pine forests of the southeastern United States. Arguments for action were strengthened by recognition that the species is capable of damaging trees and forests in its native ecosystem (T-12). Thus, a quarantine was imposed on the movement of potentially infested material out of the infected area. In retrospect, analyses indicate that the quarantine cost more than effects from the insect itself (USDA Animal and Plant Health Inspection Service 2015), partly because Christmas tree growers within the quarantine area lost access to markets and many went out of business. To our knowledge, no damage to southern pine forests has been reported even though *T. piniperda* has presumably now reached all areas of eastern North America where its ecology permits. In the Anthropocene, we can expect that there will be continuing cases of new potential pests that will challenge the decision-making of forest managers, administrators, politicians, and lawmakers. There is a need for structured transparent decision-making regarding responses to new pests that explicitly accounts for the possibility that quarantines and eradication efforts can be more costly and more damaging than the pests themselves. In Spain, the legally prescribed response to discovery of *F. circinatum* (causal agent of pitch canker) is that the entire plantation must be destroyed, symptomatic or not, and all the plant material destroyed in situ, which frequently requires burying all of the cut trees (Gobierno de España 2006). The cost of intervention can be greater than the losses in production from pitch canker. Furthermore, *F. circinatum* is now widely distributed in the northwestern Iberian Peninsula so local eradication efforts are not sensible (Pluess et al. 2012). Legally prescribed responses to pinewood nematode in Spain are even more severe (Xunta de Galicia 2017): cut all pine trees within 1.5 km and remove all susceptible host material for its local vector, *Monochamus galloprovinciales*, within 20 km. Furthermore, no wood products of any kind (logs, chips, etc.) can be moved from the area without heat treatment, and the core area of 1.5 km radius cannot be planted with pines again. This may encourage affected landowners to plant nonnative Eucalyptus or abandon the forest. The cost of response to pinewood nematode thus far has been estimated at about € 116 million in Spain and Portugal for 1999–2013 (Evans 2015). This does not include the social and economic costs of abandonment of pine forests due to lost markets and perceived risks. What if pinewood nematode in Europe turns out be a nonpest like pine shoot beetles or European wood wasps in North America (Dodds et al. 2010; Ayres et al. 2014)? At present, pinewood nematode remains largely restricted to a relatively small area in Portugal on the hot, dry edge of the distribution of *Pinus* *pinaster*. In the Anthropocene, when we can expect frequent cases of new plant-feeding organisms that might or might not become pests, we need improved capacity to consider the full suite of possible responses (including nonresponses) with consideration of (1) costs and benefits, including nonmarket costs and benefits, and (2) probabilities of different possible outcomes following different possible responses (Keeney and Raiffa 1993). The assessment of a Norwegian contingency plan for pinewood nematodes provides a positive example (Bergseng et al. 2012).

7. Better management through improved understanding of coupled human–natural systems

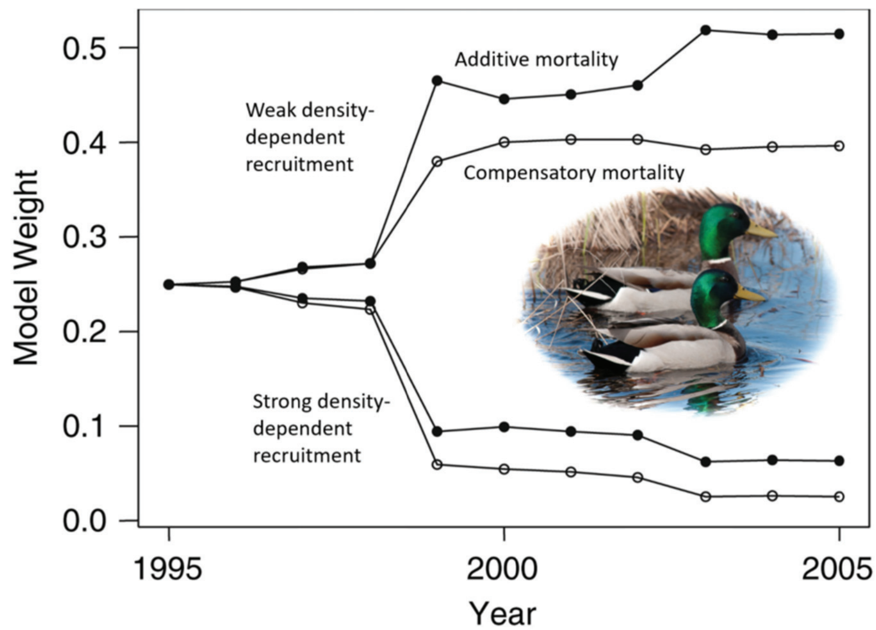
In the Anthropocene, forests and forest management are increasingly coupled with human societies, and solutions for emerging plant pests more frequently require understanding and managing the coupled human–natural systems. An example is illustrated by the challenges of paying for management of southern pine beetles (SPB) in their newly occupied range within the New Jersey Pinelands and Long Island, New York (Weed et al. 2013). In the extensive and productive pine forests of the southeastern United States, outbreaks of SPB have been managed quite effectively over the last decades with the intermittent application of "cut-and-remove" suppression to rising beetle populations (Billings 2011). Under the ideal application of cut-and-remove suppression, the discrete local infestations of highly aggregated SPB are identified from aerial surveys and mapped within weeks after they form. Then the infested trees (typically 10–50 trees per aggregation), plus a modest buffer of surrounding trees, are quickly cut by loggers, put on trucks, and taken out of the forest to nearby mills where they are sold for production of pulp, plywood, or lumber. This practice usually stops growth of the local infestation (by removing beetles from the forest and disrupting the pheromone plumes that catalyze mass attacks on trees). When most such infestations in a forest are successfully suppressed, the regional beetle population is reduced to such low levels that they can no longer employ mass attacks to kill trees, and then natural forces can maintain them at nonepidemic levels for many years without further suppression (Martinson et al. 2013). Conveniently, this management practice can pay for itself while contributing to the local economy because the cut trees have value. However, there are no mills or loggers In New Jersey or on Long Island. This makes it an expense to suppress SPB, and as a result, the globally unique pitch pine ecosystem of the northeastern United States is at risk of being functionally eliminated because the costs of managing SPB probably cannot be supported with tax dollars. Thus, it seems that the most realistic salvation for the pitch pine ecosystem would be the development of new means for deriving economic profit from cutting trees — in this case small numbers of modestly sized beetle-killed pine trees within highly populated areas. The example of SPB in its new range is not an isolated case. Managing forest pests costs money. Thus, somewhat surprisingly, economic profits from harvesting trees can promote forest health. Most examples of successful forest pest management are where healthy forests have enough value that it is sensible for communities and shareholders to invest in forest management. A correlate is that degradation of forest-based economies can be as bad for forest health as degradation of forest health is for forest-based economies. With globalization, changing economies, reductions in forest extent, and changes in the attributes of forests that are valued by people, there is a need for new ways in which forests provide economic benefits. Some traditional forest product economies involving pulp, plywood, and lumber are becoming untenable in some areas due to globalization and other forces. For example, many pulp mills are closing in North America — perhaps because they cannot compete with highly productive and efficient Eucalyptus plantations on other continents. It seems likely that maintaining forest health, and forests, in the Anthropocene will require the conception and development of new means of making sustainable profits from the goods and services provided by trees. This would be facilitated by creative thinking and improved communication among natural and social scientists, forest managers, and shareholders and engineers, entrepreneurs, and inventors. It could also help if there were means of supporting forest management through the value of ecosystem services provided by forests that are not presently market-based (Carpenter et al. 2009).

8. Adaptive management and adaptive science

Theory and data are unequivocal in projecting continuing changes in the nature and location of forest pestilence (see Fig. 1 and tactic 3). No one should be surprised by the next new pest. Forest management plans that assume stasis and certainty are a poor fit with the Anthropocene (Linder 2000; Hulme 2005; Spittlehouse 2005; Millar et al. 2007). Forest resilience is more dependent than ever before upon adaptive adjustments of forest stewardship. A potentially powerful general tactic is sometimes referred to as "adaptive management" (following Holling 1978 and Walters 1986). The core principle of adaptive management is that managers, scientists, and decision-makers collaborate such that there can be steady improvements in management efficacy through the study of outcomes from management decisions. This involves applying theory, such as it is, for making best judgements as decisions are needed and then evaluating system responses to those decisions to test and improve the theory that will inform future responses (Nichols et al. 2007). A good feature of adaptive management is the natural match with traditional ecological knowledge (Berkes et al. 2000), e.g., traditional ecological knowledge can be a source of hypotheses to be evaluated regarding system responses to perturbation *X* or management action *Y* (Horstkotte et al. 2017). There are very general reasons why adaptive management promotes resilience of coupled natural and human systems (Tompkins and Adger 2004).

Our favorite example (Fig. 2) of adaptive management is about mallard ducks because we know of no comparable examples from forest pest management. However, the management of ducks is similar to many situations in forest pest management where there are recurrent management challenges that require decisions to be made even though there is less knowledge than one would like to reliably predict outcomes. Some examples include annual predictions of outbreak risk from monitoring data, suppression of bark beetles by removing infested trees, aerial application of Bt insecticides to control an outbreak of defoliators, deployment of biological control agents, and silvicultural thinning to reduce future pest risks. Whenever these management activities are employed, there are opportunities to learn from the experience such that we have better knowledge the next time. Unfortunately, there is often little or no scientific assessment after operational management decisions, and therefore, we have little more knowledge next time than the last time (analogous to remaining mired at the beginning of the time series of knowledge growth represented in Fig. 2). Some positive examples of assessments in forest pest management include Lewis et al. (1984), Clarke and Billings (2003), Hurley et al. (2007), and Nowak et al. (2015). The mallard example illustrates a powerful tactic for learning from experience as rapidly as possible. Learning fast has obvious value for pest management in a rapidly changing world. How can we operationalize this tactic in forest pest management? Scientists could contribute by becoming better at identifying and evaluating the competing theories that underlie management decisions but are frequently implicit and possibly not thought of as theories by managers. Managers could help by working with scientists during the operational planning of actions so that the evaluation of outcomes will be most informative (e.g., by keeping good records of management actions, recording baseline data when possible, and having control plots in the landscape where actions are being applied). Administrators, politicians, and decision-makers could help by making it standard operating procedure to evaluate outcomes from forest management decisions, including decisions that were expensive

Fig. 2. An example from waterfowl management of progress by iterative assessment of competing theoretical models (modified with permission from Nichols et al. 2007). In 1995, a working group of scientists and managers identified four hypotheses regarding the response of mallard populations to harvesting by hunters. At the time, proponents of the four alternative models agreed to the compromise of initially equal model weights; later, this decision ceased to matter as the accumulating data increasingly drove model weights and the starting point no longer mattered. Each year after 1995, the models were used to predict responses of mallard abundance to whatever harvest quotas were established for the year. By 1999, population models that assumed weak rather than strong density-dependent recruitment were clearly providing better information (higher model weights). By 2003, models with weak density-dependent recruitment and additive versus compensatory mortality appeared to be providing the most reliable predictions. This pattern has been borne out by additional years of data, and now, alternative versions of this best model are being developed and similarly competed against each other (Johnson et al. 2015). Photo by Mike Ayres. [Colour online.]



and perhaps polemic. Voters, taxpayers, and shareholders could help by insisting that we learn as much as we can from actions now to inform decisions that we will inevitably face in the future. Sometimes there are structural barriers to the application of adaptive management that could be eased by administrators. For example, within the US Forest Service, Forest Health Protection is administratively separated from Research, and it is frequently no one's job to bring managers and scientists together for planning and conducting evaluations of system responses to pest management decisions. In regions of the world such as central and southern Europe where forested land tends to be a mosaic of many small landowners, the successful application of adaptive management will require communication and cooperation among many shareholders, which would be aided by the expertise of social scientists.

Conclusions

One serious limitation to implementing the strategies identified above is that resources for forest management are declining in many countries even as forests become more valuable and forest management becomes more challenging. For example, the US Forest Service budget for Forest Health plus Research declined by ~14% in the last decade (in 2016 dollars) (US Forest Service 2017; US Department of Labor 2017). Still, there is room for optimism. Budget trajectories could change with increased awareness of the growing costs of pests and the value for human welfare of good forest stewardship. With a little more information, voters, taxpayers, and lawmakers can appreciate that healthy forests more than pay for the costs of stewardship. Furthermore, forest management is a far less difficult or expensive problem than, for example, reducing global CO_2 emissions. Forestry has a long history (e.g., de Monceau 1768) with centuries of adaptive adjustments to a changing world. It is already a discipline where scientists, managers, shareholders, administrators, legislators, and voters are practiced at working together. However, meeting the challenges of managing forests and forest pests in the Anthropocene will require more and better contributions from these sectors and others. The rewards can go beyond forests per se because forest management shares many challenges with other problems in natural resource management. Examples of success in forest management can aid in other spheres (e.g., agriculture, pastoralism, fisheries, and management of water resources) that are similarly important to human well-being and environmental security and similarly threatened by global change.

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REVIEW

Planted forest health: The need for a global strategy

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Several key tree genera are used in planted forests worldwide, and these represent valuable global resources. Planted forests are increasingly threatened by insects and microbial pathogens, which are introduced accidentally and/or have adapted to new host trees. Globalization has hastened tree pest emergence, despite a growing awareness of the problem, improved understanding of the costs, and an increased focus on the importance of quarantine. To protect the value and potential of planted forests, innovative solutions and a better-coordinated global approach are needed. Mitigation strategies that are effective only in wealthy countries fail to contain invasions elsewhere in the world, ultimately leading to global impacts. Solutions to forest pest problems in the future should mainly focus on integrating management approaches globally, rather than single-country strategies. A global strategy to manage pest issues is vitally important and urgently needed.

Forests and woodland ecosystems are a hugely important natural resource, easily overlooked and often undervalued (*1*–*3*). Globally, one in six people is estimated to rely on forests for food (*3*), and many more depend on forests for other critical ecosystem services, such as climate regulation, carbon storage, human health, and the genetic resources that underpin important wood and wood products–based industries. However, the health of forests, both natural and managed, is more heavily threatened at present than ever before (*4*–*6*). The most rapidly changing of these threats arise from direct and indirect anthropogenic influences on fungal pathogens and insect pests (hereafter referred to as pests), especially their distribution and patterns of interactions.

Here we focus on the importance of pests of planted forests, which are particularly vulnerable to invasive organisms yet are of growing importance as an economic resource and for various ecosystem services. Planted forests are typically of a single species. In plantations in the tropics and Southern Hemisphere, they are usually of non-native species, such as species of *Pinus*, *Eucalyptus*, and *Acacia*. Northern Hemisphere plantations often comprise species of *Pinus*, *Picea*, *Populus*, *Eucalyptus*, and other genera, often in native areas or with closely related native species. These intensively managed tree farms cover huge areas [currently 7% and potentially 20% of global forests by the end of the century (*1*)], and they sustain major industries producing wood and pulp products. These tree genera have become natural resources of global importance, much like major agricultural crops, and are unlikely to be easily replaced.

Planted forests face various serious health threats from pests (Fig. 1). Non-native trees in plantations are in part successful because they have been separated from their natural enemies. However, when plantation trees are reunited with their coevolved pests, which may be introduced accidentally, or when they encounter novel pests to which they have no resistance, substantial damage or loss can ensue (*7*). The longer these non-native trees are planted in an area, the more threatened they become by native pests. Where the trees are of native species, they can be vulnerable to introduced pests. But the relative species uniformity of monoculture stands in intensively managed native plantation forests can make them especially susceptible to the many native pests occurring in the surrounding natural forests (*8*–*10*).

There are many opportunities to mitigate potential losses caused by pests in planted forests through exclusion (e.g., pre-export treatments and quarantine), eradication of newly established pests, and avoidance of disease through pest containment and management. Yet the lack of investment and capacity, especially in poorer countries, as well as the limited coordination of efforts at a global level, means that the impact of these tools to stem the global problem is limited. Unless this is addressed, pest problems will continue to grow and will threaten the long-term sustainability of forests and forestry worldwide. It should be recognized that the sustainable use of these tree "crops" will require the same global focus and investment to manage pest threat as that of agricultural crops.

Prevention is important but remains porous

Biological invasions of alien pests have been shown to be growing at constant or even increasing rates—and not only for those affecting trees (*4*–*6*, *11*). Few pests are ever eradicated or completely suppressed, leading to an an ever-changing and increasing number of management programs to juggle. Phytosanitary measures are the major line of defense available to limit the global movement of pests, and various international policies seek to promote them [such as the International Standards For Phytosanitary Measures No. 15 (ISPM 15)

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(*12*, *13*) that regulates the treatment of wood pallets to avoid bark beetle and wood borer invasions (*14*)].

There is evidence that strictly applied phytosanitary measures can reduce the rate of pest introductions into new environments (*12*, *14*), and this is the most cost-effective way to deal with the challenge. Some wealthy and biogeographically isolated countries in particular, such as New Zealand and Australia, have tackled this quite successfully (*15*). But there are limitations to what can be achieved realistically through phytosanitary measures at a global scale. For example, it is unlikely that poorer countries can afford to institute biosecurity actions to achieve effective exclusion to the same extent, and even where the best possible phytosanitary measures have been applied, serious new pest problems continue to occur. The accidental introduction of myrtle rust caused by *Puccinia psidii* into Australia, despite considerable knowledge of this pathogen and significant efforts to exclude it, is an apt example of the limitations of quarantine (*13*). This pathogen has now become established on many native Australian Myrtaceae, some of which are now threatened with extinction.

Traditionally, quarantine regulations have been underpinned by a listing process, in which pests threatening to a particularly country are listed after risk analyses. However, many of the most damaging forest pests introduced into new environments were unknown in their areas of origin before their introductions. For example, no listing process would have included *Phytophthora pinifolia*, which has devastated some *Pinus radiata* plantations in Chile (*16*), before its arrival. Its origin remains unknown. For this reason, contemporary thinking on phytosanitary measures has begun to focus on introduction pathways rather than on particular pests (e.g., the ISPM 15 measures discussed above) (*6*, *12*, *17*). In this regard, there is a growing realization that trade in live plants poses a particular threat that is inadequately regulated in most countries (*6*, *17*).

Quarantine can be only as effective as the proverbial weakest link in the chain. A large proportion of countries appear to have no effective quarantine in place for plants or plant products. Even where regulations are in place, the capacity to implement these effectively is often lacking. Therefore, invasive pest problems appear in these countries relatively frequently. Once a pest has become a successful invader in one region, it can serve as a source of new invasions elsewhere: a process that has been referred to as the bridgehead effect (*18*) (Fig. 2). A correlation is expected between the level of connectivity (e.g., the volume of trade) of a country and its vulnerability to invasion and potential to serve as a hub for the spread of invasive pests, but other factors also play a role in this regard (*5*–*7*).

Opportunities for mitigation

Despite the obstacles, there is reason to be optimistic about the power of established and emerging opportunities to mitigate the impact of pests. Intensive plantation forestry provides some vivid examples of how established pest problems can be confronted. To deal with the global scale and increasing intensity of the problem, however, greater global coordination and alignment of the use of the most effective tools are required.

Intensive management of forests increasingly involves planting tree species that have been selected for particular environments and traits, including resistance to certain pests. From a species base (taxa and provenance trails), it has been possible to breed and select for increasingly better properties.

One of the best examples of modern intensive tree farming is the global *Eucalyptus* forestry industry. Plantations of these trees now cover some 20 million ha, mostly in the tropics and Southern Hemisphere (*19*) (Fig. 1). *Eucalyptus* is mostly native to Australia, where more than 700 species are

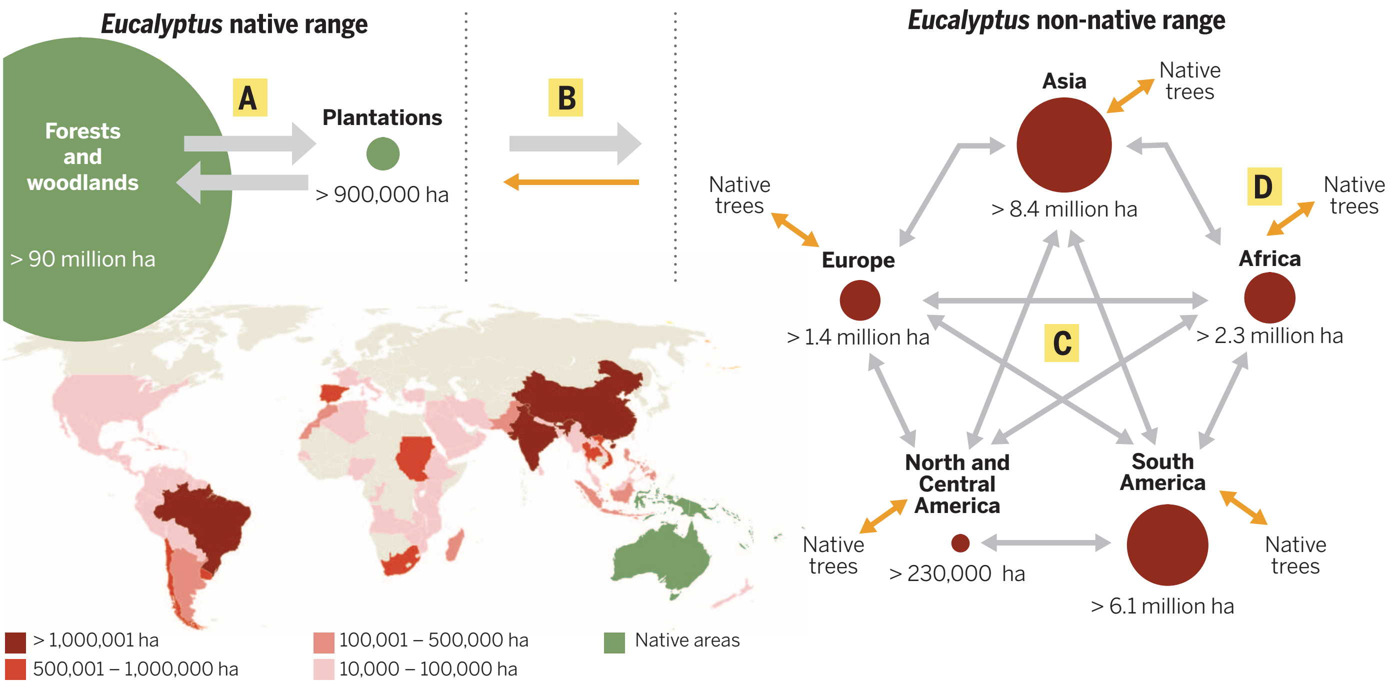

Fig. 1. *Eucalyptus* as a model to illustrate the origin and spread of planted forest pests. Plantations of *Eucalyptus* have increased from <1 million ha by 1950 to around 20 million ha today; the map shows the current distribution. These plantations experienced a steady increase of pest problems that has been accelerating during the past two decades. The origin of these pests can include the following: (**A**) Uninterrupted bidirectional spread of pests between natural and plantation areas of *Eucalyptus* in its native region. Increasing populations in plantations, and association with trade and human movement (e.g., from urban areas), increase changes in transport to other parts of the world. (**B**) Fairly large numbers of pests and pathogens spread from the native area to one or more non-native environments. Few pests spread via non-native plantations back to native *Eucalyptus* areas, but these can have devastating consequences [see, for example, the discussion on *Puccinia psidii* in the text (*13*)]. (**C**) As population numbers build up in some of the non-native environments, further movement around the world is enhanced through a bridgehead effect. The rate of this spread appears to be increasing because of the confluence of a number of processes linked to globalization (*18*, *22*) (Fig. 2). (**D**) Fairly large numbers of native pests and pathogens adapt to feed on or infect *Eucalyptus* in its non-native range. Some eventually spread to other areas of the world and can threaten *Eucalyptus* in its native range (B).

found in a wide range of environments, of which more than 10 and their hybrids are commonly planted commercially around the world today. This diversity of genetic background has provided opportunities to capture traits for fast growth in many different environments, favorable wood properties, and resistance to many different fungal and insect pests.

Vegetative propagation has underpinned the rapid growth of the *Eucalyptus* forestry industry—and similarly for poplars, pines, and acacias. Mastering vegetative propagation has made it possible to produce and intensively propagate hybrids between tree species, leading to a paradigm shift for the global forest plantation industry. It has also provided one of the most important opportunities to avoid pest problems.A classic example is the case of the stem disease known as Cryphonectria canker, now recognized to be caused by a suite of cryptic species in the fungal genus *Chrysoporthe* (*20*). In the early 1980s, Cryphonectria canker was a major threat to the sustainability of *Eucalyptus* propagation in Brazil and later South Africa. Yet the selection of clones and particularly clonal hybrids with resistance made it possible to avoid the disease to the point where it is hardly considered important today (*10*).

An approach that is increasingly contemplated is to promote resistance to pest threats by increasing diversity through mixed plantings of species rather than monocultures (*9*, *21*). From a managed forest perspective, this approach can be useful, but it is typically at odds with the needs of commercial forestry when done at a stand level. Nevertheless, introducing this form of resistance could be considered at a landscape level—for example, using clones in uniform but smaller blocks and including a diversity of genes rather than a diversity of species or even genotypes. Exploring the use of tree species and genera other than those currently used could offer further opportunities for mitigating the impact of pests and contribute to the resilience of the industry.

For introduced insect pests, biological control has provided superb solutions. Early examples of biological control in forestry date back to the early 1900s, using two introduced predators against the scale insect *Eriococcus coriaceus* on *Eucalyptus* in New Zealand and an egg parasitoid against the *Eucalyptus* snout beetle, known then as *Gonipterus scutellatus* (*22*). There have been many subsequent examples in planted forests, such as, for example, the widely applied *Sirex* woodwasp biological control using the parasitic nematode *Deladenus siricidicola* (*23*). Dealing with native insect pests is somewhat more complex, and in the absence of resistant planting stock, the application of biocides such as formulations of the insect pathogenic bacterium *Bacillus thuringiensis* and insect pathogens (e.g., *Beauvaria bassiana*) and behavior-altering semiochemical-based strategies provide opportunities (*24*, *25*). But there also remains a strong dependence on synthetic chemical insecticides that may be harmful to the environment and inconsistent with environmental certification (see http://pesticides.fsc.org).

Invest in research and innovation

Our capacity to deal with tree pest problems far outstrips the level of investment in exploring and applying these opportunities. At the outset of dealing with pest problems, we are challenged by our ability to accurately identify the pest in question. There are many examples where new pests appear that are misidentified or unknown elsewhere in the world. This is largely the result of poor or unequal levels of investment in global surveys and in our knowledge of global biodiversity. Hundreds of known pests and pathogens remain undetected, especially in poorer countries, and this problem is significantly more severe in forestry (*26*).

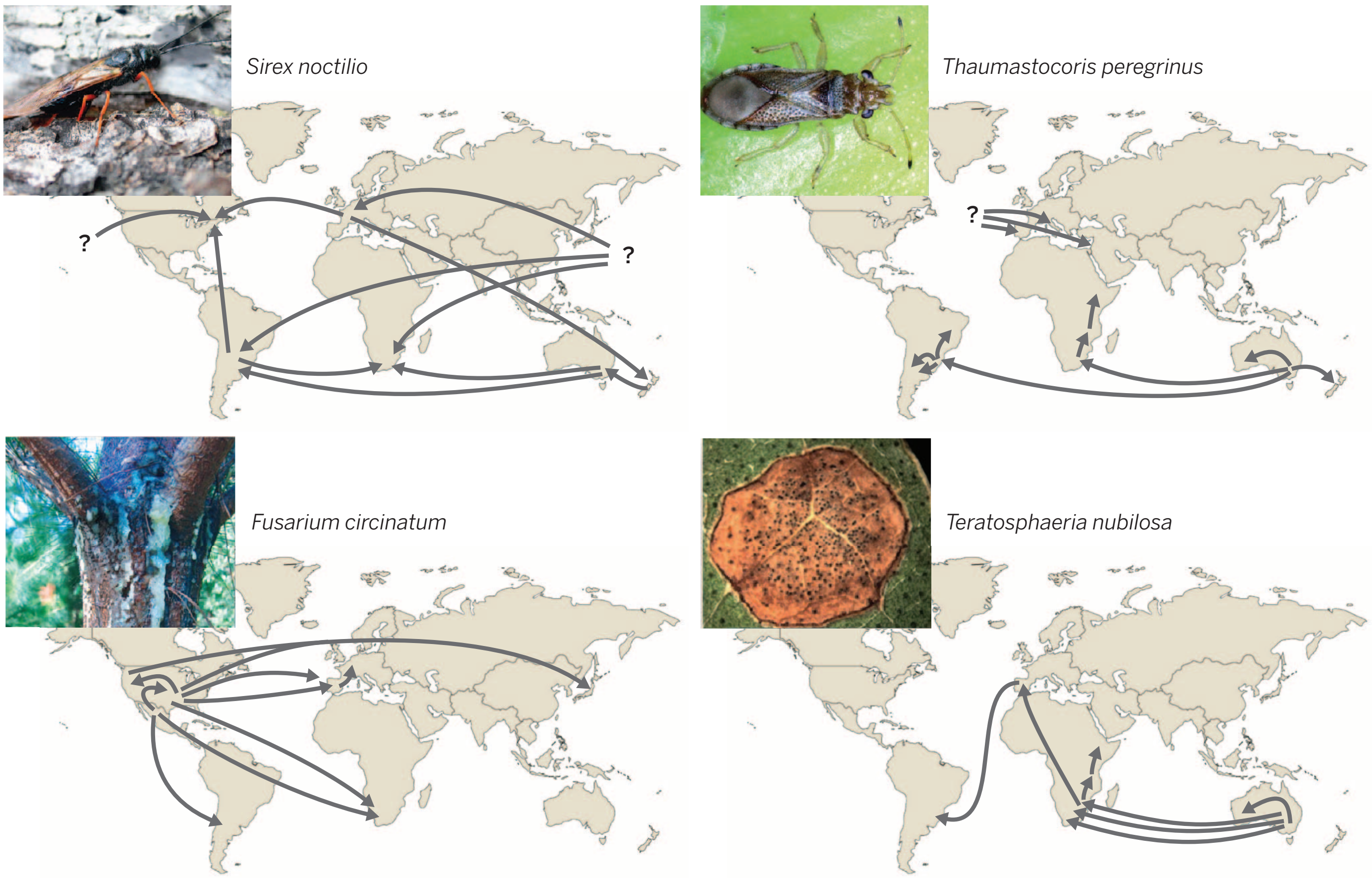

Fig. 2. Examples of invasion routes of pests of planted forests that illustrate an apparently common pattern of complex pathways of spread to new environments, including repeated introductions and with either native or invasive populations serving as source populations (*18*). Invasion routes of the pine pitch canker pathogen *Fusarium circinatum* (origin in Central America) (*39*), eucalypt leaf pathogen *Teratosphaeria nubilosa* (origin in southeast Australia) (*40*), the pine woodwasp *Sirex noctilio* (origin in Eurasia) (*23*), and the eucalypt bug *Thaumastocoris peregrinus* (origin in southeast Australia) (*41*) were determined through historical and genetic data. [Photo credits: (top left) Brett Hurley; (top right) Samantha Bush; (bottom left) Jolanda Roux; (bottom right) Guillermo Perez]

Table 1. The potential global use of various control strategies for forest pests in planted forests.

TOOLS FOR DEALING WITH FOREST PESTS	OPPORTUNITY FOR GLOBALIZATION*	POTENTIAL GLOBAL IMPACT*	CURRENT GLOBALIZATION*
Pest research tools	Red	Red	Red
Pest risk assessment	Orange	Orange	Orange
Pest information database	Red	Red	Yellow
Pathway risk management	Red	Red	Orange
National quarantine	Yellow	Orange	Yellow
Surveillance tools	Red	Red	Yellow
Incursion response/eradication	Yellow	Yellow	Yellow
Biological control	Red	Red	Orange
Genetic resources/breeding	Orange	Orange	Orange
Genetic engineering	Orange	Orange	Yellow

*Yellow = low; Orange = medium; Red = high

Research on the identification and taxonomy of forest pests, and novel ways to speed up biodiversity discovery and description (*27*), should be promoted if we hope to deal with pest problems in the future. Ideally, such efforts will be integrated with the similar needs for agricultural pests, and even for human disease.

The application of DNA-based technologies to identify forest pests has shown that these organisms often represent cryptic species that are different from those originally thought to be present. For example, the Cryphonectria canker pathogen of *Eucalyptus* in South Africa was originally treated as being in the same genus as the fungus responsible for the devastating chestnut blight disease, *Cryphonectria parasitica*. DNA-based technologies, however, very clearly showed that the fungus on *Eucalyptus* is only distantly related to *C. parasitica*, and the disease is caused by at least four different species of *Chrysoporthe* (*20*). Their correct identification is essential for the selection of resistant *Eucalyptus* clones described earlier. We easily recognize that the accurate identification of pathogens is crucial to human health and well-being, and it is equally true for the health of forests and forestry. The barcoding and typing technologies that are already available allow for much greater levels of accuracy in disease diagnosis than is currently the case.

Research in molecular genetics, including the development of tools for accelerated breeding (including marker-aided selection and genetic engineering), is already well advanced, and the genomes of the most widely planted forest tree species either have been or are in the process of being sequenced (*28*, *29*). The recent approval of the release of a genetically engineered *Eucalyptus* is an important step toward this end (*30*). The application of this technology still faces significant regulatory and technical challenges but seems set to play a major role in the industry soon. In parallel, there are also growing numbers of genome sequences available or being determined for the most important pests of these trees (*31*). The availability of these genome sequences, as well as the rapid growth of associated phenotypic and other "-omics" data, will make it possible to better understand the biology and diversity of the pests, as well as their interactions with their host trees. The continuous emergence of previously unknown pests complicates these processes and highlights the need for identification of general mechanisms of resistance, as well as the continuing nature of this research.

Semiochemicals, which are naturally occurring chemicals that influence insect behavior, can be powerfully used for the surveillance and suppression of insect pests. This tool is underused in forestry in general, and in planted forests in particular (*25*), because of a lack of capacity to study the behaviorally active compounds of pest insects and a lack of investment in this promising field. Examining the genomics of forest pests could increase the speed of discovering promising alternatives through reverse chemical ecology (*32*).

There are many positive examples of biological control of invasive alien insect pests. However, many biological control programs for forest pests have been established on flimsy foundations. Although care is often taken today to avoid nontarget effects, biological control agents are often selected with little insight into possible ecological and evolutionary determinants of their success (*23*, *33*). They can also pose significant risks to native ecosystems through nontarget effects, a fact that is broadly recognized and typically tested for today. Admittedly, the tools to understand, for example, the genetic diversity of biological control agents were not previously readily available. But these and other tools are widely available today and should become standard practice for the development of biological control programs.

A category of pests that is emerging as important is that arising from adaptation after host shifts, symbiont shifts, or hybridization (*4*, *5*, *8*, *34*). Pathogens such as *Ceratocystis* spp. that have become adapted to infect forest trees, and the cossid moths *Coryphodema tristis* and *Chilicomadia valdiviana* that have emerged as serious pests of eucalypts in South Africa and Chile, are examples of emerging novel tree pests (*34*, *35*). Earlier we described the diseases caused by *P. psidii* and *Chrysophorthe* spp., which also resulted from host jumps from native plants to *Eucalyptus*. It is particularly important to understand the mechanisms and drivers of these changes, in light of the threat that these and other similar pests pose to native forests (Fig. 1).

Global versus local solutions

Forest pest problems, not only those relevant to planted forests, inevitably affect most or all areas where a particular tree species occurs. Yet these problems are typically being dealt with in an ad hoc and localized manner in response to local damage (Table 1). There are only a few examples where groups of forest scientists have been assembled to tackle particularly important problems at large scales. The European Union has launched a number of impressive programs in this regard, such as the COST Actions [www.cost.eu/COST_Actions/fps/Actions; see Santini *et al.* (*5*) for one of the outcomes related to invasive forest pathogens], to develop the networks necessary for a more coordinated approach to key problems.

The only means by which we can realistically deal with tree pests will be through the establishment of global networks of collaboration and to share locally available knowledge [see (*22*), on biological control). The structures for such networks exist in the International Union of Forest Research Organizations (www.iufro.org), for example, but funding instruments to enable a truly global approach are nonexistent for tree pests. Thus, the time is right to raise the issue of forest pest problems to the level of the United Nations—for instance, via the United Nations Forum on Forests (UNFF; www.un.org/esa/forests/)—and thus to seek intergovernmental support for a serious problem of global relevance.

Although most forest researchers would agree readily that global research collaborations hold the key to improving a clearly inadequate capacity to deal with tree pest problems (not exclusive to managed and planted forests), answering the "who pays" question is much more challenging (*36*). Various models are in operation, but the answer most likely lies in collaborations between governments and the commercial sector. They would need to jointly take responsibility for preparedness and for the consequences of incursions, such as in the Government Industry Agreement for Biosecurity Readiness and Response in New Zealand (www.gia.org.nz/) or the Tree Protection Cooperative Program that has been jointly funded by the South African commercial sector, government, and university system for over 25 years. At present, however, it is clear that tree pest problems are made worse by the lack of clear global objectives, priorities, funding, and collaboration. This needs to be addressed, and externally supported where necessary, in developed and less-developed countries, because the overall goal will depend on a more uniform participation.

Outlook

The future of planted forests will be influenced by our ability to respond to damaging pests and the threat of biological invasions. The trends are clear, with at best a constant suite of emerging pests and sometimes a dramatically increasing rate of pest impacts. Increasing numbers of damaging hybrid genotypes and abiotic influences linked to global changes in the environment are further increasing the impact of these pests (*4*). It would be naïve to believe that local solutions such as quarantine at national borders can present a complete barrier to the global impact of pests on forests. For this reason, much greater focus will need to be placed on global strategies aimed at reducing pest movement and improving pest surveillance and incursion response, as well as optimizing the use of the most powerful tools to mitigate damage.

Genetics offers many outstanding opportunities to mitigate damage from pests, either alien invasive or native and that have undergone some form of adaptation. For managed forests and especially plantation forestry, traditional selection and breeding of species, provenances, clones, and clonal hybrids will increase in importance even further. Beyond this point, genetic engineering with genes conferring resistance to pests will be a valuable additional tool. Such genetic modification is already well advanced for *Eucalyptus* and poplar. They will also need to be managed with care, as has been true in agriculture, so as to avoid the development of resistance. The rapid decrease in the cost of generating relevant -omics data for nonmodel species, as well as inexpensive tools for gene editing such as CRISPR, will make these technologies available for more plant species sooner than previously anticipated (*37*). There are, however, valid concerns beyond the management of resistance that will require efficient platforms where the research community and various other societal interest groups can discuss the use of these technologies and collectively inform their regulation.

Pest problems in forests are well recognized and of considerable concern in many parts of the world, but this is not balanced with the investment that would be required to make a significant difference. This is a situation that should change, but funding and coordinated efforts from across a variety of disciplines and institutions would be needed to make this possible. For example, all the tools and much of the knowledge exist to develop an international database on the diversity of insects and fungi associated with trees used in plantations [there are various unlinked databases on pests and diseases, and with various levels of accessibility, that could be linked via a central database such as, for example, QBOL: Quarantine organisms Barcode Of Life (www.qbol.org)]. Such a database could be powerfully linked to metadata related to host use, natural enemies, climate, surveillance tools and information, and more.

It is not possible to predict which tree pest problems are likely to be most important and damaging in the future. The so-called unknown unknowns and black swan diseases will remain a challenge (*35*). The appearance of new pests can still surprise local industries and governments, and responses are often erratic and inadequate. Through a more coordinated global investment in relevant research, it should be possible to respond more rapidly and mitigate problems more effectively in the future. There are also increasing opportunities to capture the imagination and support of the public, to create awareness, and to expand the capacity for surveillance beyond the limited number of specialists, through the implementation of citizen science and crowdsourcing mechanisms.

Bill Gates recently called for new thinking about global systems to deal with human infectious disease problems in order to avoid a global health disaster (*38*). Although the situations for tree pests and human disease are not fully comparable, there are many similarities. Tree health specialists as well as funding agencies concerned with global tree health should learn from these. In particular, it should be recognized that although the impact of tree health disasters is experienced locally, the drivers of their emergence are global. This makes uncoordinated local efforts to slow the overall emergence all but futile. Our capacity to deal with serious tree pest problems will remain minimal unless we can find the support and vision to launch a more global and holistic approach to study these problems and to implement mitigation strategies.

A global strategy for dealing with pests in planted forests is urgently needed and should include:

• A clearly identified body with the mandate to coordinate and raise funds for global responses to key pests and to monitor compliance with regulations.

• A central database on pests and diseases of key forest plantation species.

• Shared information on tools for and information from the surveillance of pests and pathogens in planted forests.

• Identification of measures with potentially high global impact for pest mitigation, and support for the development and sharing of capacity.

• More-structured systems for facilitating biological control, including global sharing of knowledge, best practices, and the selection of agents (organisms).

• Protection of the genetic resources of the key forest plantation genera.

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