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CONCEPT PAPER

Forest pests and their management in the Anthropocene[1]

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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.

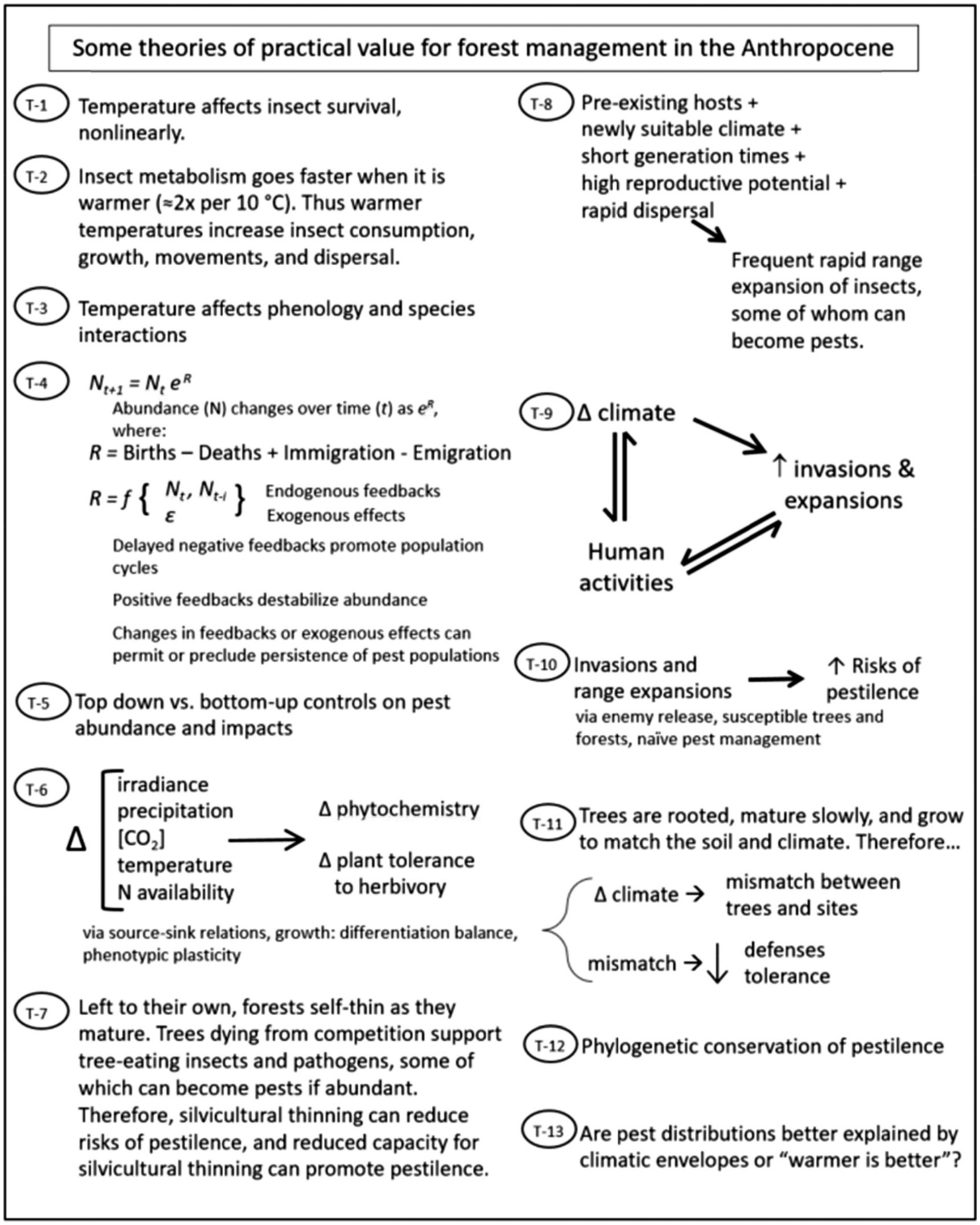
1. Growth of practical theory that is transportable among forests and regions

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

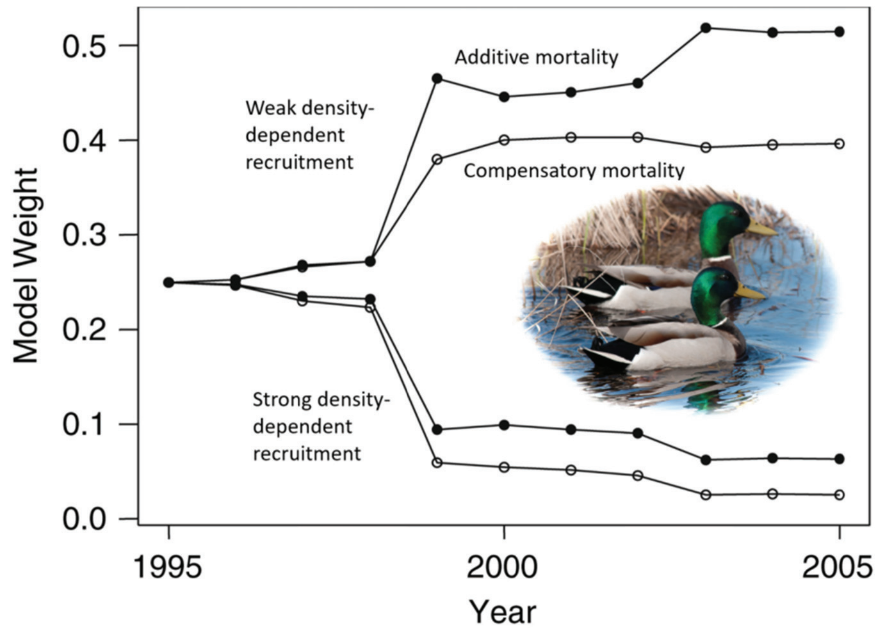
In the Anthropocene, forests and forest management are increasingly coupled with human societies, and solutions for emerging plant pests more frequently require understanding and managing the coupled human–natural systems. An example is illustrated by the challenges of paying for management of southern 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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