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The Global Forest Health Crisis: A Public Good Social Dilemma in Need of International Collective Action

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Abstract

Society is confronted by interconnected threats to ecological sustainability. Among these is the devastation of forests by destructive non-native pathogens and insects introduced through global trade, leading to the loss of critical ecosystem services and a global forest health crisis. We argue that the forest health crisis is a public good social dilemma and propose a response framework that incorporates principles of collective action. This framework will enable scientists to better engage policymakers and empower the public to advocate for proactive biosecurity and forest health management. Collective action in forest health will feature broadly inclusive stakeholder engagement to build trust and set goals; accountability for destructive pest introductions; pooled support for weakest-link partners; and inclusion of intrinsic and non-market values of forest ecosystems in risk assessment. We provide short-term and longer-term measures that incorporate the above principles to shift the societal and ecological forest health paradigm to a more resilient state.

Keywords: biological invasions, natural resource policy, global change, climate change, conservation of biodiversity

Defining the Problem

The under-recognized forest health crisis

The Anthropocene has given rise to a chorus of wake up calls from increasingly alarmed scientists about the state of our environment and extreme threats to ecosystems that sustain human life. Along with other natural systems central to human wellbeing, such as the atmosphere, soils, and water systems, the world's forests—which cover 30% of its land area and account for 45% of terrestrial carbon stocks (162)—are at an ecological tipping point (234). Globally, we are witnessing widespread loss of critical forest habitats and species.

Among the drivers of such losses, biological invasions by forest pests (insects and pathogens) that kill or otherwise severely reduce productivity of trees at landscape and regional scales have become all too common (55, 193). These biological invasions constitute a societal grand challenge that needs to be addressed simultaneously with a long list of synergistic issues and crises: climate warming; food and income insecurity; environmental destruction; loss of biodiversity; and emerging human and animal infectious diseases (132, 183). Importantly, the ongoing intercontinental exchange of forest pests threatens not only the forests themselves, but also the myriad ecosystem services that both natural and planted forests provide, regulate, and support: biodiversity, cultural heritage, agricultural sustainability, clean water, carbon sequestration, renewable energy, and raw materials (21, 129, 140, 214).

Biological invasions are primarily driven by human activity and amplified by advances in technology and trade. With the rise of modern global trade in the 20th century, humans began introducing highly destructive, novel insects and pathogens to evolutionarily unprepared hosts on new continents at an ever increasing rate—a pattern that is expected to continue well into the future (85, 89, 178, 193, 200, 201, 203). These encounters led to devastating, landscape-transforming epidemics affecting iconic tree species, including: pine wilt disease in Eurasia (*Bursaphelenchus xilophilus*, vector *Monochamus* spp.; 160); white pine blister rust in North America (*Cronartium ribicola*; 151); Dutch elm disease (*Ophiostoma novo-ulmi*, vector *Scolytus* spp.) and chestnut blight (*Cryphonectria parasitica*) in Eurasia and North America (143); and myrtle rust (*Austropuccinia psidii;* 47, 86) throughout Australia/Oceania and the Paleotropics. This crisis is not unique to native forests (235); for example, European wood-wasp (*Sirex noctilio*) and its pathogenic fungal symbiont threaten the sustainability of exotic pine plantations in South America (43), Africa and Australia (108).

The crisis of forest insect and pathogen invasions is pervasive. Functional extinctions of canopy tree species, lasting landscape-scale shifts in forest composition and structure, carbon release, and economic loss from forests are now commonplace (68, 144). In the US alone, the 15 most destructive non-native insects and pathogens cause as much tree mortality as fire, and currently threaten an estimated 41% of standing biomass and two thirds of forested land area (68, 179). Tens or hundreds of megatonnes of carbon are being released annually (e.g. 12.5 mt/y in the United States alone; 184) by the decimation of trees that are recognized as ecological and/or cultural keystone species such as oaks (*Quercus* spp.; 42), ashes (*Fraxinus* spp.; 44, 78, 107, 124, 175), beeches (*Fagus* spp.; 29, 63, 64), multiple species of cedars and cypresses (family Cupressaceae; 93, 117, 165, 225), laurels (family Lauraceae; 91 and 165), and plane trees (*Platanus* spp.; 114), to name just a few. North America has also done its part by exporting highly destructive insects and pathogens abroad, such as *Ceratocystis platani*, which kills planetrees in Europe and the Middle East (137, 212, 219), and pine wilt disease (160), the red turpentine beetle (*Dendroctonus valens*) and fall webworm (*Hyphantria cunea*) in East Asia (280, 282). Even as the fallout from host species loss reverberates through ecosystems and economies, new destructive insects and pathogens continue to accumulate (8, 22, 144, 196). Meanwhile, concomitant losses of biodiversity and positive feedback with climate change amplify the vulnerability of forests to new biological invasions (12, 54, 94, 112, 130, 182, 186).

The societal, cultural, and economic impacts of insect and pathogen invasions are as far-reaching and profound as their ecological consequences. In the past, they have included loss of culturally iconic trees and the displacement of entire communities of people and industries. For example, Rapid ‘Ōhi‘a Death (caused by *Ceratocystis* spp.), laurel wilt disease (LWD, caused by *Raffaelea lauricola*), and the emerald ash borer (*Agrilus planipennis*) have had negative impacts on indigenous cultural practices and heritage (16, 44, 75, 76, 154). In Japan, habitat for the culturally important matsutake mushroom (*Tricholoma matsutake*) has been negatively affected by pine wilt disease because of the decline of its pine hosts (65, 218). Rural poverty of

Appalachia (US) is well-known, but the loss of 3.5 billion American chestnut trees on 3.6 million hectares of land is seldom recognized as a contributor to that poverty (e.g. 149).

The forest health crisis is also one of human equity because it has the greatest socioeconomic impacts on emerging economies in low, lower-middle, and upper-middle income countries (LIC, LMIC and UMIC, respectively), which often harbor biodiversity hotspots (199). Economic growth and improved standards of living in emerging LMIC and UMIC economies rely on global trade and foreign investment (4, 83, 188), but these same forces put them at increased risk of pest invasions (55), particularly as trade opens and partnerships realign (reshoring) in the southern hemisphere (5, 199). At the same time, many of these same countries lag in detection capacity (46). Meanwhile, rural communities in poorer countries rely directly on forests and agroforestry for significant portions or their income, water, and food, putting them at direct risk from insect and pathogen introductions that arise from global trade (38, 166, 187, 232). Even in the more affluent countries, many rural and regional economies are heavily dependent on small to large-scale forest industries, and forest health issues that lead to loss of livelihood therefore put them at a significant risk of economic and social instability (e.g. 23, 121).

Unfortunately, and despite the scale and scope of these devastating consequences, these issues seldom penetrate public discourse on trade and the environment (e.g. 6). For example, the word “forest” has not been used in the US President’s State of the Union Address since 1990 and “invasive” has never been used (20); nor have invasive forest insects and pathogens been included in the agendas of the 2021 COP15 to the Convention on Biological Diversity (https://www.cbd.int/meetings/COP-15) or COP26 UN Climate Change Conference (https://ukcop26.org), despite an explicit focus on forest restoration. Indeed, it is hard to imagine an effective forest restoration policy that does not explicitly account for biological invasions, which are a neglected but substantial driver of biodiversity loss (192).

The unrecognized crisis of forest insect and pathogen invasions is epic in its proportions, and demands a proportional global response. Due to the interconnectedness of the modern world, unchecked insect and pathogen invasions in one country can lead to more introductions through international spillover and bridgehead invasions (12, 87, 172, 235). Without significant, coordinated action on a global scale, the perpetual onslaught caused by destructive invasive organisms will continue to transform forest ecosystems and all that depend on them worldwide. Insect and pathogen invasions also threaten planted forests (235), reforestation, and afforestation efforts, and assisted migration campaigns currently being undertaken to combat climate change (26, 177), particularly as nursery stock is a prime vector for destructive pathogens of woody plants (22, 36, 136).

Clearly, the crisis of forest insect and pathogen invasions demands urgent action. There is a critical need to understand the complex societal drivers of insect and pathogen invasions and for solutions that explicitly consider diverse societal contexts (193). With adequate resources, research capacity, time, and willingness to take bold action, many forest health problems appear solvable. Yet, society continues to struggle with novel invaders in familiar and unfortunate ways that increasingly point to the inherently social dimensions of the challenge. Using a collaborative interdisciplinary reasoning approach (164, 134), we developed consensus on the major challenges preventing policy success in the realm of forest health and invasive species, summarized the state of the science in the context of the consensus position, propose an integrated framework for addressing forest health threats, and provide an action plan for addressing the major challenges. This approach, typically used in the context of interdisciplinary and transdisciplinary team science, relies on iteration of ideas and convergence towards shared understanding of scientific language, knowledge, and perspectives. We employed this approach over the course of two large meetings – the Idea Café at Plant Health 2020 (American Phytopathological Association) and a symposium at the 2021 North American Forest Insect Work Conference.

Below, we present a case for viewing the forest health and invasive species problem as a public good social dilemma that will require a socially and ecologically holistic, well-integrated, equitable and adaptive approach to stem the flow of novel introductions and help the world to manage established insects and pathogens more effectively in threatened ecosystems. Without such change, the crisis will continue to have devastating consequences for society and its ability to achieve environmental sustainability, fight poverty, and safeguard human health. To address this need for reconceptualizing the global forest health crisis, we highlight important opportunities for, and barriers to, practical solutions within social and political spaces.

Declining forest health is a public good social dilemma in need of international collective action

Forests are an undeniable part of the world's collective heritage, and must be recognized as such if we are to properly protect them. Insofar as they regulate carbon cycling and contribute to global biodiversity, forests are known to constitute a common-pool resource on a global scale (sensu 170). Although protecting forests from invasive pests is mutually beneficial to all (63), the world has failed to agree on an effective strategy to achieve this goal. We argue that in order to adopt a more effective strategy, the problem must first be recognized as a public good social dilemma, which creates a basis for adoption of collective action.

We argue that the failure of the world's current institutions and policies to effectively safeguard forest health stems from a poor alignment with the public good nature of the problem and intrinsic value of forests and forest health. The majority of invasive forest insects and pathogens arrive in North America, the European Union and other free-trade hubs in solid wood packaging materials and live plants imported for the nursery trade (146). To address the pest threat, member countries of the World Trade Organization (WTO) have negotiated rules that attempt to balance measures aimed at reducing the risk to local forest tree species against economic gain (50, 169, 278).

Unfortunately, the result of these negotiations has been international agreements aimed at restricting rather than empowering member countries to impose effective embargos, quarantines, and phytosanitary protocols to protect biodiversity and natural resources (22, 193). These agreements include the 1995 Sanitary and Phytosanitary Standards (SPS) Agreement (278), which delegates power to the International Plant Protection Convention (IPPC), first entered into in 1952 (58, 193) to develop standards. Even assuming general compliance with the standards that have been set under these agreements, the number of non-native insects and pathogens that have become established and the damage they cause continues to accumulate worldwide (25). Furthermore, as explained below, there is little to no accountability for violators or those responsible for pest introductions. The current wording, lack of urgency in adopting stronger rules, and insufficient enforcement illustrate how economic interests are weighed heavily while the high non-market value of forests is largely overlooked in international negotiations.

A current and key challenge to achieving an adequate level of deterrence for exporters and importers of destructive insects and pathogens lies in insufficient accountability (22, 193). The major concern of the WTO agreements is to "ensure that strict health and safety regulations are not being used as an excuse for protecting domestic producers" (279), ostensibly balancing trade with health; clearly, the main interest of the organization is trade and commerce. At the level of the exporter, under current agreements, such as they are, behavior can adapt to regulatory actions by exploiting weakly-enforced ports or intermediates in the supply-chain, thereby undermining phytosanitary action (57). Furthermore, the ability of national plant protection organizations (NPPOs) to provide adaptive responses is challenged by the fact that a rule applied to mitigate a risk in one country cannot be any more strict than another applied for a comparable risk in another country (D. Bednar, personal communication).

The state of global forest biosecurity in world trade is akin to a prisoner's dilemma (220), where an accountability deficit, combined with domination of the decision-making process by commercial interests, stifles cooperative resolve to protect forest ecosystems among trade partners. The current, dominant strategy in the negotiation of world trade relations permits an ever-increasing volume of high-risk trade items, including packing materials, wood products, and live plants, without adequate and proportional penalties to more effectively deter introductions of new insects and pathogens. These same principles are likely to generally apply to emerging multilateral and bilateral agreements, because the primary interests considered in renegotiation of trade agreements are the potential impacts on domestic and export markets. Continued prioritization of access to overseas markets over the sustainability of domestic natural resources ensure that the failures of the international phytosanitary status quo—namely, its insufficient accommodation of phytosanitary actions, sanctions, and enforcement—go unremarked and uncorrected. This is despite the fact that the most widely adopted phytosanitary standard (ISPM 15), which is only partly effective, has clearly demonstrable net value, and shows that stronger precautionary policy would greatly add value (138).

The IPPC rules themselves, and their implementation, are driven by the mandate to prevent protectionism. As a direct result, the rules do not decrease direct risks to an acceptable level. Mutual agreements to adopt or permit stronger enforcement rules would have a smaller net global cost when factoring in avoided impacts on forests, particularly when accounting for non-market losses, i.e. most ecosystem services (138, 193). However, this strategy is perceived as less desirable due to the current failure of commercial interests to recognize that a reduction in the rate of new insect and pathogen introductions is sufficiently beneficial to warrant the short-term monetary sacrifices it will entail. As a result, the world faces a phytosanitary public good problem that feeds the global forest health crisis.

To address this public good problem, we emphasize the importance of developing solutions that facilitate collective actions among various actors at local, national, and international levels. Lessons learned from successful efforts to address similar problems in the management of common-pool resources and public goods suggest that the sustainability of healthy forests cannot be ensured solely through innovations of the free market or the powers of state control (170). We argue that an integrated approach to combat the forest health crisis should embrace a collective action framework (12, 90, 171) that incorporates the following principles of stakeholder engagement and empowerment (12, 45, 63, 277):

- Agreement on a shared goal among stakeholders
- Trust for coordinated action among stakeholders
- Pooling resources to support weakest-link stakeholders
- Locally-adapted rules and solutions formulated by stakeholders
- Sanctions and other concrete accountability measures to deter violators and tools for conflict resolution among stakeholders
- Monitoring to track progress of ongoing efforts, supported by stakeholder engagement

Situating these principles at the core of forest health policy interventions is critical due to the complexity, scale, and conflicts of interest at the center of this crisis. Many common-pool resources and public goods, such as fisheries and weedy plants, have been managed successfully by applying the above principles (12, 135, 170). As with these other public goods, non-native insects and pathogens do not respect political borders, and effective management of invasion risk requires contributions from all the diverse parties with interests in forest ecosystems. However, the investment cost of solutions to the forest health crisis are borne differently across various international, state, and local government actors, private interests, industries, and individual landowners, while the benefits (i.e., the public goods) are inherently nonrivalrous and realized on a global scale. Together, these attributes make the forest health crisis a social dilemma (90). Success at tackling such a public good social dilemma—and ultimately realizing a reduction in invasive insect and pathogen introductions and more effective control of active outbreaks—will require a baseline, threshold amount of investment and sustained collective action from all stakeholder groups across scales (12, 90).

There are numerous tactical solutions that can help address the forest health crisis in small but important ways in the short term. But to solve the public good social dilemma in the long term, sustained collective action that incorporates the aforementioned principles of stakeholder engagement and empowerment will require coordination among a multitude of stakeholders whose worldviews, perspectives, and interests are often largely at odds (i.e., it is a “wicked problem” sensu 277). It will also require a dynamic political process for effective and equitable negotiations and compromises among diverse stakeholders. We argue below for the importance of establishing an agenda for forest policy reform that recognizes how conflicting economic, political, social, and cultural interests form the landscape in which short- and long-term solutions could be developed (57, 192, 196, 197, 201).

An Agenda for Reform and the Constraints it Faces

Efforts at each stage of the policy development process—(1) agenda setting, (2) policy formulation, and (3) implementation—are critical for shaping the trajectory of policy (191) to combat the forest health crisis. As discussed below, this crisis presents unique challenges at each stage of the process that include: (a) institutional constraints; (b) the difficulty of generating political will to protect forest health through a traditionally economic paradigm; and (c) the current lack of empowerment of stakeholders outside of predominant power structures. Strategic political solutions are needed to navigate those challenges.

Agenda setting

In the agenda setting stage (104), framing the debate about forest pest invasions as part of the global forest health crisis will have significant influence on policy outcomes. To foster mutual trust and agreement on a shared goal from an early stage, a viable forest health effort would engage stakeholders beyond historically dominant forces of agricultural lobbies to include actors such as indigenous nations, the forestry industry, and forest and biodiversity conservation organizations worldwide. Effective, persuasive (i.e. emotive), and evidence-driven messaging that underscores the high non-market value of the global forest biome and its connection to environmental sustainability, and even agricultural productivity, is also critical to motivate receptive participants in the policy arena.

Paradigm-shifting societal and environmental disturbance events, such as the COVID-19 pandemic, provide an opportunity for the public and their leaders to reassess their value system and implement reforms (63), perhaps shifting the window of viable policy solutions toward collective action approaches. The pandemic also provided insights into how government at different levels of organization responded and the human response to a common threat globally. Interest in popular high-profile initiatives (e.g. the Trillion Tree Initiative, the Paris Agreement on Climate Change, and the Convention on Biological Diversity) can also be leveraged to call attention to the impending forest health risks that lax biosecurity might present to the wrong trees planted on poor sites or in disease-prone ecological arrangements. Such biosecurity risks add to other ecological (26) and social (71) concerns raised by so-called nature-based climate solutions, such as a focus on trees over people, highlighting the need for collective action approaches to a complex social and ecological problem. For these reasons, both social and ecological dimensions of forest health concerns must be elevated to the level of internationally mainstream ecological discourse. To be effective, we believe the new forest health agenda for reform must incorporate the following four principles in collaboration with a broad international coalition:

- Strengthening international biosecurity to prevent introductions
- Integrated pest management that strategically applies the most effective, evidence-based and data-driven tools for each specific insect, pathogen, ecosystem, nation, and

cultural and management context to contain and suppress future, introduced and established pests

- Significant, sustained, and comprehensive research funding to bolster and improve the ability to survey, detect, and manage insects and pathogens and to increase forest resistance and resilience
- A change in policy stance from the current fundamentally reactive paradigm of managing current or legacy crises to a proactive approach designed to prevent and minimize them

Policy formulation

In the policy formulation stage, the policy goals listed above must adapt to constraints, which include the cultural and institutional contexts of advocacy efforts and political and governmental processes that will narrow the range of feasible solutions. Currently, much public perception of invasive species could be characterized as invasion fatigue (e.g. 237), reminiscent of COVID-19 pandemic fatigue. There has even been a rise in biotic invasion denialism stemming in part from suboptimal agreement and communication about the lexicon of invasion biology that justifies fatigue and normalizes invasion in popular media, and even among some ecologists (194, 204). Stakeholder engagement can address such apathy by contributing to mutual trust, agreement on a common goal, perceived self-efficacy and empowering the public to make a difference (41, 204), as recently demonstrated by the popularity of the “Don’t Move Firewood” campaign in the US in response to invasions by wood-boring insects (193). Other constraints of the current institutional ecosystem include ineffective, lethargic, and fundamentally reactive domestic responses to insect and pathogen invasions; research funding structures that favor agricultural plant health over forest health research; and politically driven roadblocks to cooperation (e.g. 87).

Current forest protection policy is most critically constrained by a lack of recognition for the broader cultural, aesthetic, and intrinsic values of forestlands (e.g. 127, 157), including functioning and resilience of diverse agroecosystems, water resources, urban shading, soil quality, and erosion control, among many others. The value of intact, healthy forest ecosystems mostly accrues outside of a market context but is conventionally monetized in policy discussions, arguably counteracting potential societal priority to protect them. In a recent estimate of the costs of all types of biological invasions, a superficial list of forest insects and pathogens only accounted for < 1% of records in a global database, while still accounting for 25% of total annual costs at $43.4 billion USD (49). Given the non-market value of forests, this economically focused approach to identifying possible solutions for minimizing the risk of biological invasions fails to align with broader societal and sustainability goals.

Implementation

In the implementation stage, policies that build trust and increase coordination among the public, scientists, forestry and wood product professionals, and policy makers are critical to cultivate a resilient and equitable institutional ecosystem (1). Implementation decisions are currently guided by economic risk assessment. Such assessments must account for high levels of uncertainty because, unlike plants and large animals, invasive forest insects and pathogens are often cryptic and commonly moved as asymptomatic endophytic infections and infestations (119, 205), many are also not well-known in their native range or are often new to science (22, 34, 118, 126), and they typically behave in new and unpredictable ways in their expanded range (169, 193). In most cases, it is nearly impossible to determine exactly when and where the insect or pathogen was introduced, contributing to a lack of accountability (40). These sources of uncertainty imperil efforts to build trust and can even be exploited by special interests to block proactive biosecurity measures. They also make it difficult to impose trade restrictions under current international agreements (40, 169, 193).

Worldwide, the implementation of forest health monitoring and response skews heavily in favor of insects and pathogens that impact agriculturally important and/or non-native timber species (72). The downstream effects of this skewed focus can be irreversible, as exemplified by the stories of governmental response to laurel wilt disease (LWD) in the US and myrtle rust in Australia (Sidebar). Engagement of indigenous nations, the forestry sector, and recreation agencies, as well as support from private interests for protecting native species, could have had the potential to more effectively sustain the implementation of policy programs that reduce risks to forest biodiversity in the US, Australia and around the globe.

A Collective Action Framework to Protect Forest Health

A number of terms, frameworks, and concepts to describe strategies to minimize the impact of biological invasions have been reviewed elsewhere and accompanied by substantial disagreement about how to frame the invasion process (11, 88, 122, 140, 146, 190). Such frameworks tend to be strongly based on invasions by plants, while falling short of effectively accommodating microbial pathogens and insects that also cause widespread damage to forests (173, 174, 236). Invasion context may include social, economic, cultural, and ecological considerations (Fig. 1).

An integrated framework to address forest pests should incorporate: (1) more effective biosecurity to prevent new introductions; (2) increased monitoring for early detection and improved preparedness for rapid response to outbreaks (30); (3) management, including silvicultural treatment (e.g., sanitation and salvage), chemical suppression, behavioral and biological control; (4) development of host resistance and (5) management of forests to promote ecological resistance to invasion. These approaches can be mapped into successive introductory, establishment, and spread phases of invasion (17) (Fig. 1). Intervention in the earliest stages before an invasive pest becomes well-established and widespread, and investment in ecological resistance and resilience are the most cost effective as part of the integrated framework (Fig. 1). In the remainder of the section, we discuss how incorporating collective action principles in the stages and modes of integrated forest health management can help overcome social and political impediments to promote societal resilience in the face of forest health challenges caused by invasive species.

Overhauling biosecurity agreements and measures to prevent introductions

Biosecurity is the most effective way to combat invasive species, but it is the central social dilemma in forest health protection. Ideally, communities, governments, corporations, and nations will “think locally, act globally” to minimize the volume of international and interstate commerce to what is strictly necessary for societal functioning. Such changes in consumer behavior would reduce carbon emissions and revitalize local economies, and could be encouraged by a full accounting of costs (101) or green labeling (193). However, global trade contributes substantially to human wellbeing and cannot be eliminated. Therefore, we advocate for proactive scrutiny and an ultimate reduction of trade in commodities that present high risk to forests and promotion of native landscaping. In both the near and long term, we must apply collective action principles to reduce uncertainty, strengthen phytosanitary measures, and prevent introductions.

In its early stages, collective action does not need to be centrally coordinated. Reciprocal and/or graduated sanctioning of repeat offenders is an organic strategy to foster cooperation for mutual benefit in international dilemmas (i.e. "tit-for-tat" sensu 9) and a key principle of collective action (11). To this end, progress could be made when individual countries step up enforcement and impose sanctions on importers that violate phytosanitary measures or introduce insects and pathogens. In 2017, the US Bureau of Customs and Border Protection (CPB) increased its enforcement of wood packaging regulations under US Code Title 19, which has likely encouraged US importers to improve sanitation. Through executive action, such policy implementation could be made even more aggressive to further discourage the importation of destructive insects and pathogens. NPPOs in trade partner countries would then be incentivized to do the same, leading to a reciprocal reduction in the rate of new invasions and evolution of international cooperation to clean up trade pathways (9). Eventually, trade partners (key international stakeholders) would be compelled to revise the international rules and agree on a new, tougher set of sanctions.

Tree-SMART trade (https://www.caryinstitute.org/science/tree-smart-trade) has been presented as a simple framework to immediately reduce the risk of forest pest invasions. The policy initiative includes: Switching to pest free packaging; Minimizing outbreaks with early detection and rapid response; Augmenting international pest protection programs; Restricting high-risk live plant trade; and Tightening enforcement of penalties for non-compliant shipments. In addition to stepping up customs enforcement, the USDA APHIS "Not Authorized Pending Pest Risk Assessment" (NAPPRA) rule or a similar designation by NPPOs outside of the US could be specifically extended to live plants and untreated wood products derived from plant species with native relatives in the importing country. Such plants and wood products are more likely to be vectors of as-yet unknown pests to the importing country's trees (84, 85, 89, 145). A designation of this kind could be permitted under a broad interpretation of SPS Article 5.7, which allows provisional restrictions in the absence of concrete data. In the medium term, a more complete picture of pre-invasion risks would allow scientists to better engage policymakers and trade partners to build trust, set common goals and take coordinated action to implement strategic quarantines.

Stakeholder-driven cooperative programs can be expanded to preemptively complete the picture of pre-invasion risks (40, 57). A reduction in uncertainty would provide a concrete basis for risk reduction, common rules and goals, and targeted improvement of biosecurity. In particular, surveys of sentinel native trees and close relatives planted abroad support pre-invasion detection for high-risk species and commodities (60, 152, 161, 172). Once properly and formally integrated into biosecurity frameworks, early-warning gardens in new plantings, botanical gardens, urban forests, and plantations will provide precious lead time to impose quarantines under SPS Article 5.7 and develop tools and techniques needed to support effective detection and response efforts. Recently such efforts have resulted in the pre-invasion detection of potential future threats and evaluation of the potential risk they pose (80, 215). Efforts are underway through Botanic Gardens Conservation International (BGCI) to coordinate an International Sentinel Plant Network (ISPN; www.plantsentinel.org) for pre-invasion detection and facilitation of the transfer of pre-invasion monitoring data to NPPOs.

International and interdisciplinary collaboration also holds promise to identify and quantify risks. For example, the Pine Pandemic Preparedness Plan in the southeastern US, which aims to address the potential threat to the US “fiber basket” in the southeast, is a community-driven example of relevant research aimed at quantifying and mitigating risk prior to invasion, and more such efforts are needed (79). For commercial species (*Acacia*, *Eucalyptus*, and *Pinus*, etc.) there is a wealth of data abroad on host performance and genetic resources in trials and operational plantations; the consolidation and analysis of these data would rapidly advance efforts to overhaul risk assessments for planted forests (233) while also selecting resistant stock, a significant additional benefit of such analyses.

A second component of Tree-SMART trade is the use of pest-free packaging material (pallets, crates, dunnage, etc.) in international shipments (145). This will require significant trust-building, goal-setting, and resource sharing among stakeholders due to potential impacts on allies in the forestry sector and wood products industry. Phasing out wood packaging could threaten local economies and industries. For example, sustainable Salicaceae forestry in Patagonia, Europe, Asia, and the Middle East relies on demand for pallet materials (13). Given the importance of these stakeholders, potential conflicts of interest will need to be addressed by applying collective action principles for the “long view” of forest health. With stakeholder support, processed wood (e.g., oriented strand board), recycled plastic, and even fungi could be used as pest-free alternatives (116, 213).

Early detection

Globalization is a fundamental aspect of modern society, but universal responsibility for the social dilemma it entails to protecting natural systems is not readily apparent or perceived as tractable to individuals. Biosecurity policies in the US and EU, for example, currently rely heavily on port inspection and interception, the bottlenecks of pest introduction pathways. But even under relatively intensive surveillance strategies, pests invariably slip through. Regulations intended to reduce pest importation on live plants are estimated to have been less than 50% effective in the US; and only a fraction of species present in pathways worldwide have been intercepted, while some commonly invading taxonomic groups are hardly detected at all (59, 95, 139, 222). Importantly, most established species had never been regulated or were unknown to science prior to becoming a threat to forest ecosystems.

Once novel insects are recognized as having been introduced or identified as a high risk for introduction, traps baited with volatile chemical attractants are the most widely used management tool for monitoring them in managed forests. Attractant-baited traps can be highly effective for detecting and delineating most bark and ambrosia beetles, Lepidoptera, and Hymenoptera, but only somewhat effective for wood boring beetles, and of little utility against most sap-feeding insects (185). Air and soil traps combined with molecular tools are also increasingly employed for fungal and oomycete pathogens (37, 158, 221). For years, remote sensing has been used and has become an important tool to detect the impacts of insects and pathogens, and recent advances in technology are poised to revolutionize aerial detection. Although the above techniques are increasingly employed across agencies and levels of organization, by the time an invasive pest is formally discovered, it is frequently found to have evaded detection for years or decades (199). This lag in detection can be attributed to the cryptic nature of many forest insects and pathogens, a lag in expression of symptoms, tree mortality and/or lethargic institutional response, population dynamics, and adaptation (2, 18, 31, 193, 216).

Clearly there is a need for even more coordinated effort, common goal setting, and pooling of resources to ramp up surveillance efforts in order to keep pace with the continually rising volume of international trade (57). Collective action has the potential to greatly improve capacity to detect pests in time to achieve a successful response. For example, in the US, such efforts have been exemplified by the USDA-APHIS Cooperative Agricultural Pest Survey (CAPS). Foremost, global analyses suggest severe undersampling and lagging detection of invasive species in LICs and MICs, and/or in the Neotropics, Paleotropics, Asia, and Oceania (39, 92, 222) where invasions are expected to increase in the future (199). There is a need for aid, resources, and technical assistance from more wealthy nations to address this gap; in fact, such resource pooling is mandated in the SPS agreements (57).

NPPOs must strengthen surveillance to increase the probability of early detection of invasive insects and pathogens in live exported nursery plants, wood packaging, and forests on public and private land. In the short-term, national border customs organizations (e.g. US Bureau of Customs and Border Protection, CPB) could be supported in dedicating higher levels of surveillance to wood packaging were it designated as a high risk import by NPPOs.

In the long term, the collective action principle of stakeholder engagement could be broadly applied to improve detection of pests both domestically and internationally. For example, USDA-APHIS coordinates surveillance and response with states through CAPS and supports and coordinates the Plant Pest and Disease Management Disaster Prevention Program and US Sentinel Plant Network (www.sentinelplantnetwork.org). Such inter-institutional arrangements might be expanded to give a broader set of stakeholders a voice on local, regional, and national plant boards. With support from wealthy countries and funding agencies, emerging sources of data from new technologies and international partners could be merged and exchanged among NPPOs for use in risk assessment to detect pest threats in LICs, LMICs, and UMICs. As such efforts are scaled into the future, trust will build and the costs of emerging technologies will decrease significantly. However, currently access to some data repositories on pest occurrences and detections, such as the National Plant Diagnostic Network in the US, is highly restricted in order to protect commercial interests, embodying the conflict of interest at the center of the social dilemma, making risk assessment difficult, and thus imperiling local resources.

Rapid response

In a classic social dilemma, the weighing of competing interests and mismatches in perceived risk among stakeholders delays response to pests after detection (22, 63). These mismatches stem from a lack of common goals, inadequate support for weakest-link actors, and failure to accommodate stakeholder-driven local adaptation (11). For example, when regional forestry or wood products industries are affected, quarantines that restrict trade in timber can pose direct conflicts of interest among stakeholders (22, 32); on the other hand, when the immediate risk affects less economically important hosts, institutions are slow to act (see side panel).

Successful response can often be credited to collective action (11). Agreements, organizations, and cross-agency coordination programs have achieved success in the rapid response realm. To expand rapid response efforts in the near term, governing bodies could relax criteria authorizing the use of emergency funds to mobilize interagency responses to introductions and broaden criteria for imposing quarantines. Existing cross-agency and international frameworks and agreements could serve as a bridge to more centralized national and/or international pest management authorities.

In the US, Congress could increase funding for the cooperative APHIS “Tree & Wood Pest” Program (TWPP), which currently focuses heavily on suppression and eradication. The TWPP has been funded at the same annual rate (~$55-60 million) since it was decreased by ~33% in 2012 (https://www.usda.gov/our-agency/about-usda/budget). The TWPP and specialty crops programs could support more expansive cooperative response by increasing funding and/or by taking advantage of cutting-edge tools, including mobile citizen science platforms, remote sensing, genomic surveillance, and rapid molecular detection (100, 148, 161).

In the longer term, centralized guidance modeled on the Centers for Disease Control and Prevention (CDCs) or Federal Emergency Management Agency (FEMA) in the United States, the European Centre for Disease Prevention and Control (EU), and World Health Organization would enable more rapid detection and coordinated response (18, 63, 170). Such a model is outlined briefly in the section on resilience below. The ability of institutional frameworks to mount robust responses would be bolstered by more comprehensive stakeholder involvement, trust in decision-making processes, and an agreed-upon set of goals that serves the wider community (side panel).

Pest management

Once invasive insects and pathogens have begun to spread across a new landscape, classical tactics for suppression, including chemical and microbial pesticides, mating disruption, and silvicultural manipulation, can be employed in planted and natural forests as part of an integrated pest management framework to contain them or reduce their impact. However, once established and spreading, many insects and pathogens are notoriously difficult to contain or suppress, especially in a matrix of public and private lands and in the midst of a society with mixed opinions on the appropriateness or acceptability of the tactics employed. Operationally, the success of suppression efforts depends on the type of pest, management context, and degree to which institutional frameworks incorporate and accommodate the principles of coordination, trust, setting common goals, and local adaptation driven by stakeholder engagement and empowerment.

Through cooperative interagency efforts including the TWPP in the US, spread and damage have been greatly reduced in some cases by setting goals to prioritize problematic invasive insects and by employing a range of adaptive suppression tactics. These include the model success story of integrated approaches including aerial suppression via microbial pesticides targeted by pheromone-trap triggered models, biological control, quarantine, and pheromone-based mating suppression to contain *Lymantria dispar* (217, 141). Although recent reviews and meta-analyses cast doubt on the general effectiveness of salvage and sanitation (153), these silvicultural pest management strategies have contributed to successful local eradication and containment of Asian longhorned beetle *Anaplophora glabripennis* in the US (141, 217) and control of white pine blister rust in Korea (131) and China (283). In a combined silvicultural and semiochemical technique, bark beetles such as *Pityophthorus juglandis*, the vector of the fungus associated with thousand cankers disease of black walnut, can be lured with semiochemicals and/or artificially stressed “trap trees” that can then be removed (159, 206). Insects such as *Adelges* spp. (e.g. hemlock woolly adelgid) and emerald ash borer, as well as some fungi, are amenable to chemical control in urban and suburban landscapes and parks.

Chemical suppression is effective when supported by significant investment and stakeholder consultation for its use, but in practice, its application is often limited by scale, environmental costs, and social perception. While effective at scale in heavily managed forests and/or locally in urban contexts, suppression remains expensive and requires intensive and sustained effort, sometimes over decades, to yield success. In China, Japan, and Korea, biweekly aerial pine wilt disease suppression campaigns across millions of acres of forest utilize neonicotinoids, the same chemicals often used to drench or to inject individual trees for emerald ash borer in urban areas in the US (202, 223, 281). Questions have been raised regarding the environmental cost, particularly to pollinator populations, of the aerial applications in pine forests in Asia. On the other hand, convergence of local interests around the control of emerald ash borer in urban areas has allowed for some success in mitigating loss of urban tree cover while boosting perceptions of self-efficacy (sensu 41) among citizens.

Suppression of invasive species is perhaps the most controversial management mode in public discourse. The intensity and high level of stakeholder involvement required from private landowners can contribute to a perceived lack of self-efficacy, fatigue and apathy regarding the larger issue of invasive species. Domestically, interagency working groups such as the National Invasive Species Council (NISC) and nongovernmental organizations such as The Nature Conservancy (TNC) have been instrumental in promoting self-efficacy through outreach programs such as: “Don’t Move Firewood” to limit the spread of bark and wood boring beetles (211); and “PlayCleanGo” (https://playcleango.org/), which reduces transmission of soilborne pathogens.

Biological control has yielded substantial success against a number of invasive forest insects, especially defoliators (e.g. 69, 98, 150, 224). For example, biological control of winter moth (*Operophtera brumata)* has been successful (56). However, as we explain below, the effective development and use of natural enemies to regulate established invasive pests would greatly benefit from a more rigorous consensus among the scientific community, regulatory agencies, and the public on the specific contexts where it is practical, useful, promising, safe and/or ethical in realistic management contexts.

Biological control has many strengths and benefits as a tool to manage established pest populations. Natural enemies possess the valuable properties of being self-dispersing and reproducing, complementarity to other management tactics, and functioning in density-dependent fashion (56, 97, 120, 195). They are also sustainable in that they undergo natural genetic feedback, often with faster generation times than the pest, thereby preventing loss of efficacy due to pest evolution (103, 105, 120).

Despite these positive attributes, there are important circumstances when biological control has not been adequate to protect trees, particularly in the case of pathogens (181). This is especially true when host trees show both little resistance and little tolerance to the pest to allow for natural enemy buildup or the pests are protected within plants from many natural enemies (115, 128). Unfortunately, such instances include some of the most damaging, ecosystem-altering invasive organisms that are currently arriving in disproportionately high frequencies (8). Likewise, biological control has had relatively little success against invasive bark and wood-boring insects (but see 108), and even less against insect-phytopathogen complexes (181). Additionally, the utility of natural enemies can be constrained by higher trophic interactions and climatic mismatches in their introduced zone (198, 227).

Breeding for host resistance

Host resistance breeding can provide an environmentally safe, bottom-up approach to combat established and future threats (203) at any stage of invasion (Fig. 1). In tree species most affected by novel pests, there is often a low frequency of genetically resistant individuals, and these will be vital in any attempt to recover the species and associated ecosystems. When properly organized and resourced, breeding programs offer potential to establish populations of genetically resistant trees in a timely manner (208, 209). Classical and biotechnology-assisted breeding includes the use of markers, transgenic and gene-editing technologies (51) and emerging tools for rapid phenotyping methods (e.g. 226). Importantly, in a collaborative approach, host breeding efforts could leverage germplasm from sentinel plantings abroad (60, 152), as well as citizen scientists domestically (109, 229). Introducing trees with improved resistance may also synergize with biological control by facilitating population build up of natural enemies.

The USDA Forest Service (USFS) has benefited from investment in successful resistance breeding programs for more than 50 years, some of which involve other federal, state, county, private and indigenous tribal partners and cooperators in a multitiered stakeholder-driven approach. USFS programs have recently developed resistant populations of ecologically, economically, and culturally important species, including *Acacia koa, Pinus* spp., and *Chamaecyparis lawsoniana*, which is expected to be unlisted from its threatened species designation in the near future (53, 66, 207, 209). Disease resistant populations of *Castanea dentata*, *Ulmus americana*, and more recently *Fraxinus* spp., are also in various stages of development, approval, deployment, and improvement (27, 125). Indigenous tribes are taking a lead role in the deployment of resistant populations, including establishment of seed orchards (R. Sniezko, unpublished).

The continued and growing utility of host resistance to manage the forest health crisis into the future will depend on broad application of collective action principles, including agreements to prioritize target species based on economic, cultural, and ecological importance (156, 179). Success will also depend on long-term, pooled investment in infrastructure to develop and deploy resistance into the landscape (18, 27, 70, 163, 203, 209) if it is to successfully incorporate both host and pathogen diversity (229).

Much-need public support for breeding is mounting (113, 163), particularly for transgenic resistance, including the major breakthrough with American chestnut (*C. dentata;* 192, 180, 230), which, as a famously functionally extinct species, offers opportunities to garner future support for host breeding (229) and beyond (27). Another success story, improved resistance of whitebark pine (*P. albicaulis*) to *C. ribicola*, has led to an integrated, collaborative, cross-institutional species restoration plan which has helped garner public support (157). Highlighting the need for collective action, successful development and deployment depend on long-term commitment to maintain programs over time and to maintain resistance in response to pest evolution and the introduction of new pest populations (27, 210).

Resistance and Resilience of Forests and Society to Major Invasive Pest Disturbances

The relative degree of resistance and resilience that forests and societies have in the face of forest insect and pathogen invasions strongly depends on the social institutions governing natural resources, and their relationships among human communities and one another. These include, but are not limited to, property rights and the associated constraints; political arrangements associated with forest policy; forest product market mechanisms and supply chains; and traditional and local knowledge and practices related to forest management and conservation (15, 28, 82, 251). The resistance and resilience of forests and society can be enhanced by incorporating collective action principles into forest management systems (63) and by improving the ability of various stakeholders to take proactive steps to protect forest health and to mount a robust response to forest insect and pathogen invasions. Effective engagement requires strategic communication plans that fully account for the resources, living conditions and cultural values of stakeholders; that employ communication for education and social behavior change; and that make effective use of social marketing using technology and media (157).

Resistance and resilience of forest ecosystems

Natural disturbances play a critical role in maintaining biological diversity at multiple scales. However, disturbances caused by invasive pests lead to permanent community shifts, including costly functional extinctions and losses of productivity (96). Resistance and resilience against disturbances caused by invasions are therefore central to a holistic approach to protecting forests from invasive species (see 153).

Forest stand and landscape composition and structure, which can be modified by management practices, have implications for pest outbreaks (153) and, therefore, invasion biology. Diversity is integral to bolstering and sustaining forest resistance and resilience to biological disturbances (153), including invasive species. Genetic and structural diversity of plant communities at stand and landscape scales can be promoted by management based on natural disturbance regimes and at the landscape scale by using locally adapted material and by applying traditional ecological knowledge (10, 14, 52, 112, 153). Diversity promotes resistance to pest invasions through spatial and temporal variation in resource availability (especially with specialist pests and pathogens) and promotes recovery of ecosystem functioning and services through stand and landscape heterogeneity and redundancy of functional roles and life histories (153, 251). For example, susceptible species are sometimes protected by neighboring non-hosts (associational resistance); the accumulation of invasive pests is diminished by higher forest tree diversity; and pest damage increases with lower non-host diversity (36, 42, 94, 110, 112). A lack of top-down regulators like natural enemies (142) in degraded or low-diversity forests is also thought to be an important factor in the facilitation of biological invasions (102, 203). Diverse ecosystems are also more likely to rebound because there are other tree species present to replace the ones eliminated by the invaders.

From a social and international perspective, the management of forest ecosystems for resilience and resistance to invasions hinges on resourcing biodiversity conservation efforts, fostering cooperation, acknowledging economic realities and accommodating sustainable land use worldwide. It was thought for a long time that lower reporting of invasions in the tropics was due to biotic resistance, but recent scholarship suggests invasive species are underreported in these often heavily deforested and environmentally degraded, and/or economically poorer parts of the world, i.e. the weakest links, highlighting the need for investment from resource-rich trading partners (39) and free exchange of information. Moreover, success in the fight against climate change, which threatens forests with increased rates of both biotic and abiotic damage, may not be attainable without successful conservation and reforestation efforts across the world. Thus, efforts to ensure global forest resilience to biotic invasions should rely on a resilient global coalition that includes international cooperation between LIC, LMIC, UMIC, and wealthy nations, pooling resources to support research, monitoring, and management and building trust to identify local challenges, priorities, and knowledge.

Institutional and societal resilience

We have outlined stopgap measures to begin to turn the tide on the forest health crisis. Below, we discuss how (1) coalition building, (2) robust research and development funding, and (3) reorganization of NPPO models will be needed to sustain these measures.

Above all, achieving strong international biosecurity, integrated domestic pest management, sustained and comprehensive research funding and a proactive policy stance will inevitably require building an inclusive global coalition. The effectiveness and longevity of such a collective action strategy will hinge on leadership, collective action principles (11, 63, 90, 170), and the ability of scientists and advocates to develop and communicate the costs and benefits of proactive vs. reactive policy (e.g. 138) through a compelling, emotionally engaging narrative. Such efforts must emphasize the significance of forests to the public and policy makers.

An effort to better connect local-level stakeholders will be central to addressing the crisis. In the US, making a case for the support of indigenous advocates may be an effective strategy to place the intrinsic value (e.g. 157) of natural systems front-and-center in agenda setting and policy formulation. Indigenous nations and rural populations bear the brunt of tree losses worldwide and have unique, locally adapted monitoring expertise (14, 189). Sporting and outdoor enthusiasts should also be natural advocates because of their stake in fishery, wildlife, and foraging habitat, as demonstrated by their involvement in restoration of Port-Orford Cedar threatened by invasive root rot (R. Sniezko, pers. obs.). Recruiting, training, and collaborating with citizen scientists could also constitute a powerful human resource for advocacy, monitoring and implementation of restoration efforts (123, 176). Labor unions and the forestry industry might become natural allies that could mobilize calls for improved trade regulations; the profitability of domestic production could rise as a result of tougher biosecurity measures. Cooperatives like the Pine Pandemic Preparedness Plan and Swiss Needlecast Cooperative

(Oregon State University) have demonstrated the potential support of industrial stakeholders for forest health preparedness, research and development.

Collective action could leverage existing efforts and infrastructure of cities and municipal governments, non-governmental soil and water conservation districts, and a vast network of stakeholder-based groups and foundations in the US and beyond (e.g. American Chestnut Foundation, Walnut Council, International Oak Council, Whitebark Pine Ecosystem Foundation, Sugar Pine Foundation, etc.). In free markets, support of certification groups such as the Sustainable Forest Initiative and American Tree Farm System in North America, or the Program for Endorsement of Forest Certification Schemes (PEFC) and the Forest Stewardship Council (FSC®) in Europe could also lead to incentivization of proactive monitoring and pest management on private lands (81). Bringing such a diverse set of stakeholders together behind a common set of priorities and goals is essential for collective action but will require careful messaging and reconciliation among conflicting interests.

International efforts to train, build capacity, and encourage interdisciplinary research and cross-training are also needed. Within the science community, a common vision, pooling of resources, and investment from private and public sources will be required to support essential research activities to protect forest health. In recognition of the highly interconnected nature of modern forest health threats, coordinated academic collaboration will be required among tree geneticists and breeders, pathologists and entomologists (111, 235), ecologists, foresters, sociologists, anthropologists, psychologists, communication scholars, political scientists, economists, and even public health specialists (18). Unfortunately, funding for the fields of forest pathology and forest entomology and for host resistance breeding programs have severely declined in the US in the last 30 years (19, 24, 67, 96, 231). Funding for forest health research will need to be strengthened to facilitate a coordinated effort across research institutions to hire faculty and graduate students in pathology, entomology, human dimensions of natural resources, and other plant health fields to focus on forest health issues (3). Such programs may be non-existent, especially in LICs and LMICs, and for economically unimportant tree species, further highlighting the need for resource pooling to support weakest-link partners.

Most importantly, it is high time to rethink existing structures and operations of forest health protection organizations, i.e. forest NPPOs. In recognition of the need for stakeholder-driven, multitiered and centralized coordination, a system of Centers for Forest Pest Control and Prevention (CFPCPs) was recently proposed as an organizational model for the implementation of an integrated set of evidence-based forest pest management strategies among academic, national, local, tribal, and non-government stakeholders and agencies in the US (18). We advocate that such models be bolstered and adopted not only in the US but also by other governmental and non-governmental bodies. The International Union of Forestry Research Organizations (IUFRO) and the Food and Agricultural Organization (FAO) of the United Nations (e.g. through established regional forest invasive species networks) could be integral to coordinating efforts among CFPCPs in a role analogous to the World Health Organization.

CFPCPs would also play an analogous role to the CDCs to build trust with the public through focused science communication (194).

As a model of collective action, the centralized authority would facilitate coordination across multiple agencies and levels of government to implement the collective action forest health framework outlined above. NPPOs will need to take coordinated action on international scales via efforts that could be spearheaded by IUFRO, governing bodies such as FAO and major influential NGOs such as the North American Invasive Species Management Association, the Environmental Defense Fund, The Nature Conservancy, Intergovernmental Platform on Biodiversity and Ecosystem Services, Natural Resources Defense Council, and International Union of Conservation of Nature and Natural Resources (IUCN).

A Strategy for Advocacy to Shift the Paradigm

A fundamental paradigm shift is essential for long-term, sustainable forest health policy solutions (Fig. 2). Ultimately, it will be imperative to elevate forest health to a more prominent position in national and international political, societal, and scientific discourse (77). In addition to public engagement through collaborating NGOs, concerted effort will be required among the lobbying arms of the national and international societies in relevant fields of scholarship to advocate for funding and support (73). If advocates prioritize short- and long-term solutions such as those we have outlined, the societal, economic, and political paradigm around forest biosecurity and the health of natural ecosystems will eventually shift to an improved state characterized by proactive policy approaches that positively reinforce resilient forests and help to foster a more sustainable society (Fig. 2). If not, positive feedback within the interconnected web of societal and environmental crises that have come to characterize the Anthropocene will only increase their intractability.

Destructive invasions by insects and pathogens of forest trees are sometimes misperceived as solely a forest health issue. In reality, the state of health of our forests has significant ramifications for other important issues, e.g. climate change, economic development, public health, and social equity. However, this reality has not yet led to broad support for forest health among policy actors and institutions whose interests align very well with the issue. While the aforementioned NGOs have the expertise to influence policy decisions at the international level to address the forest health crisis, their agendas are filled with other intimately connected forms of environmental degradation, which can lead to a relative loss of focus on the issue of invasive forest insects and pathogens. It will be essential to emphasize that healthy forests protected from, and resilient to, invasive insects and pathogens will be critical to maintaining a healthy biosphere.

One way to make a case for the importance of integrating forest health into efforts to address more high-profile global grand challenges is to shift social perception of what is acceptable and possible over time. Through policy and pressure, short-term measures such as those detailed above have the potential to promote perceptions of self-efficacy (41), generating a groundswell of support to attract NGOs, parliaments, and politicians to the forest health crisis as an issue to rally around. For example, emphasis on health of urban forests and their importance may offer an effective public engagement strategy due to relevance for most of the public in terms of the myriad cultural, ecological and economic values and benefits of urban forests, and the large costs to municipalities and residents of losing urban forest cover (e.g. 61, 155). Lessons from previous social dilemmas reveal the power of such a public groundswell. Outcry brought universal condemnation to the damage caused by a widely used insecticide (DDT) due to the optics of declining charismatic songbirds such as the Spotted Towhee, and non-target insects such as the monarch butterfly (33). Similarly, people who came of age before the 1990s or even more recently remember a time when tobacco smoking was common in public spaces and not considered a public health issue; today, thanks to public health advocacy, the opposite is true throughout the world.

Forest health specialists will be tasked with a protracted fight to make forest protection a societal priority by linking forest health to public health and presenting it as the global public good that it is. Only the most diverse, forward-thinking, and inclusive environmental advocacy leadership will be capable of sustaining that fight, building trust, and facilitating negotiations among stakeholders. It is imperative that academics commit themselves to championing diversity, building trust and communication with stakeholders and landowners, collaborating outside their field and advocating with agency staff, parliaments, and NGOs, while continuing to do research focused on the crucial questions relating to how to identify, prevent, and manage invasive species. Agency staff may use their existing authority to prevent as many new pest invasions as possible and to effectively manage established threats while intentionally cultivating a societal and political environment conducive to trust among scientists, stakeholders, and public servants. The public may call on congresses and parliaments to strengthen trade regulations and to provide funding for agencies and academics to do their jobs effectively and proactively. Likewise, it is essential that NGOs use their lobbying power to advocate for the urgency and importance of the forest health crisis before it becomes an even greater catastrophe. Like the connected problem of climate change, the mobilization of an unrelenting and fully inclusive, multi-tiered international movement to make “think global, act local” a societal norm is the principal long-term challenge posed by the global forest health crisis (170, 171).

Summary Points

- The challenge posed by biotic invasions is inherently international in scope and universal in consequence
- The forest health crisis is intimately connected with many of the most prominent and existential grand challenges to ecological and economic sustainability of the Anthropocene
- We have outlined short term actions that can be taken to move toward a more sustainable stable state for the world’s forests and society

- Even the most genuine and well-resourced efforts to address the forest health crisis will eventually fail if they do not fully embrace the collective action principles outlined in this work
- In order to reduce the rate of introductions, effectively detect and respond to new invasions, manage established insects and pathogens, and bolster resistance and resilience of ecosystems and society to forest health threats, there is a need for trust, coordinated cooperation, continued public education and awareness, a common vision, locally adapted strategies, and shared investment

Future Issues

- To achieve a common vision and to build and sustain the collective will to do so, leaders must empower, engage, and listen to a broader stakeholder base
- Due to the fundamental role that resilient forests play in the health of the biosphere, functioning of global economies, and viability of local communities, a case can be made for integration of forest health efforts into companion advocacy related to empowering local and indigenous communities, LICs and MICs, the conservation of biodiversity, and collective action to address climate change
- Policy must also take into account the intrinsic, cultural, and non-market value of forest ecosystems in risk assessment and proactive decision making processes

- Ultimately, stakeholder empowerment will lead to a wider societal embrace and collective will for stewardship of biodiversity and a more resilient society

Statement of Author Contributions

All authors contributed to the conceptualization and writing of the manuscript. As explained in the main text, the multidisciplinary project conceptualization process occurred over the course of two meetings (Plant Health 2020 and 2021 North American Forest Insect Work Conference) and two years of email discussions and smaller virtual meetings among the authors. The manuscript writing and editorial process also included multiple rounds of feedback as well as written and intellectual contribution from all the authors.

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References cited

1. Adams DC, Olexa MT, Reynolds T. 2018. Invasive Alien Species Policy: Incremental Approaches and the Promise of Comprehensive Reform. *Drake J. Ag. Law* 23
2. Aiko S, Duncan RP, Hulme PE. 2010. Lag-phases in alien plant invasions: separating the facts from the artefacts. *Oikos* 119:370-378
3. Alavalapati J, Allen JA, Baker TT, Belli KL, Hayes JP, et. al. 2019. Forest Health Alliance: University Forest Resources Programs Perspective. *The Forestry Source* 24:17
4. Alvarado R, Iñiguez M, Ponce P. 2017. Foreign direct investment and economic growth in Latin America. *Econ. Anal. Pol.* 56 176–187
5. Anonymous. 2021. The new rules: A changed world. *The Economist*. Oct. 9, 2021
6. Anonymous. 2021. Making trade greener: When environmental protection turns into trade protection. *The Economist.* Oct. 9, 2021
7. Anonymous. 2021. Treedemic: Britain’s trees are being felled by diseases. *The Economist.* Oct. 9, 2021
8. Aukema JE, McCullough DG, Von Holle B, Liebhold AM, Britton K, Frankel SJ. 2010.

Historical Accumulation of Nonindigenous Forest Pests in the Continental United States. *BioSci.* 60:886–897

9. Axelrod R, Hamilton WD. 1981. The evolution of cooperation. *Science* 211:1390–1396
10. Ayres MP, Lombardero MJ. 2018. Forest pests and their management in the Anthropocene. *Can. J. For. Res.* 48:292–301
11. Bagavathiannan MV, Graham S, Ma Z, Barney JN, Coutts SR, et al. 2019. Considering weed management as a social dilemma bridges individual and collective interests. *Nat. Plants* 5:343–351
12. Bale JS, Masters GJ, Hodkinson ID, Awmack C, Bezemer TM, et al. 2002. Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Global Change Biol.* 8:1-16
13. Ball J, Carle J, Del Lungo A. 2005. Contribution of poplars and willows to sustainable foresry and rural development. *Unasylva* 56(221). https://www.fao.org/3/a0026e/a0026e02.htm
14. Berkes F, Colding J, Folke C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecol. Appl.* 10(5):1251-1262
15. Berkes F, Turner NJ. 2006. Knowledge, learning and the evolution of conservation practice for social-ecological system resilience. *Human Ecol.* 34:479
16. Billie JE. 2014. Beetles Killing Our Tu Lee Must Be Stopped. *The Seminole Tribune*. Feburary 26. https://seminoletribune.org/beetles-killing-our-tu-lee-must-be-stopped/

17. Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, et al. 2011. A proposed unified framework for biological invasions. *Trends Ecol. Evol.* 26:333–339
18. Bonello P, Campbell FT, Cipollini D, Conrad AO, Farinas C, et al. 2020. Invasive Tree Pests Devastate Ecosystems—A Proposed New Response Framework. *Front. For. Glob. Change* 3:2
19. Bonello P, Hadziabdic D, Rizzo D, Tomimatsu G, Beattie G. 2020. Bolstering Forest Pathology to Ensure a Robust Forest Health Community for the Future. *Phytopathology News* 54(5)
20. Borevitz B. 2021. Searchable State of the Union. http://stateoftheunion.onetwothree.net/
21. Boyd IL, Freer-Smith PH, Gilligan CA, Godfray, HCJ. 2013. The consequence of tree pests and diseases for ecosystem services. *Science* 342
22. Brasier CM. 2008. The biosecurity threat to the UK and global environment from international trade in plants. *Plant Path.* 57(5):792-808
23. Bratkovich S. 2004. Forests of Indiana: their economic importance. US Department of Agriculture, Forest Service, Northeastern Area, State and Private Forestry Technical Report NA-TP-02-14. https://www.in.gov/dnr/forestry/files/fo-2004_Indiana_Economics_pub.pdf
24. Brawner J, Coyle D, Eckhardt L, Enebak S, Gandhi K, et al. 2019. Forest Health Alliance: The Research Perspective. *The Forestry Source* 24(11):16
25. Brockerhoff EG, Liebhold AM. 2017. Ecology of forest insect invasions. *Biol. Inv.* 19(11):3141-3159

26. Brundu G, Pauchard A, Pyšek P, Pergl J, Bindewald A, et al. 2020. Global guidelines for the sustainable use of non-native trees to prevent tree invasions and mitigate their negative impacts. *NeoBiota* 8(61):65-116

27. Buggs RJA. 2020. Changing perceptions of tree resistance research. *Plants, People, Planet* 2:2–4

28. Buttel FH. 2020. Social institutions and environmental change. In *The International Handbook of Environmental Sociology* ed. MR Redclift, G Woodgate. Northampton, MA: Edward Elgar Publishing. https://doi.org/10.4337/9781849805520

29. Cale JA, Garrison-Johnston MT, Teale SA, Castello JD. 2017. Beech bark disease in North America: Over a century of research revisited. *For. Ecol. Manag.* 394:86–103

30. Campbell FT, Schlarbaum SE. 2014. Fading Forests III: American Forests What Choice Will We Make? Report, University of Tennessee. http://treeimprovement.utk.edu/FadingForests.htm.

31. Cappaert D, McCullough DG, Poland TM, Siegert NW. 2005. Emerald ash borer in North America: a research and regulatory challenge. *American Entomologist* 51 (3):152-165

32. Carnegie AJ, Pegg GS. 2018. Lessons from the incursion of myrtle rust in Australia. *Annual review of Phytopathology* 56:457–478

33. Carson R. 1962. Silent spring. Houghton Mifflin Harcourt.

34. Carter PCS. 1989. Risk assessment and pest detection surveys for exotic pests and diseases which threaten commercial forestry in New Zealand. *NZ J. For. Sci.* 19(2): 353-374.

35. Castagneyrol B, Giffard B, Péré C, Jactel H. 2013. Plant apparency, an overlooked driver of associational resistance to insect herbivory. *J. Ecol.* 101: 418–429.

36. Černý K. 2021. Invasive oomycetes in Czech forest nurserires and their management. Presentation at the Internatinoal Union of Forest Research Organizations 7.03.07. Biological invasions in forests: trade, ecology and management. September 23, 2021

37. Chandelier A, Hulin J, San Marin G, Debode F, Massart S. 2021. Comparison of qPCR and Metabarcoding Methods as Tools for the Detection of Airborn Inoculum of Forest Fungal Pathogens. *Phytopathology* 111(3). doi: 10.1094/PHYTO-02-20-0034-R

38. Chechina M, Neveux Y, Parkins JR, Hamann A. 2018. Balancing Conservation and Livelihoods. *Conserv. Soc.* 16: 420–430.

39. Chong KY, Corlett RT, Nuñez MA, Chiu JH, Courchamp F, et al. 2021. Are Terrestrial Biological Invasions Different in the Tropics? *Annu. Rev. Ecol. Evol. Syst.* 52.

40. Clarke DA, Palmer DJ, McGrannachan C, Burgess TI, Chown SL, et al. 2021. Options for reducing uncertainty in impact classification for alien species. *Ecosphere* 12(4):e03461

41. Clarke M, Ma Z, Snyder SA, Floress K. 2021. Factors Influencing Family Forest Owners' Interest in Community-led Collective Invasive Plant Management. *Environ. Manag.* 67(6):1088-1099

42. Cobb RC, Haas SE, Kruskamp N, Dillon WW, Swiecki TJ, et al. 2020. The Magnitude of Regional-Scale Tree Mortality Caused by the Invasive Pathogen *Phytophthora ramorum*. *Earths Future* 8

43. Corley JC, Lanyschner MV, Fischbeib D, Martínez AS, Villacide JM. 2019. Management of *Sirex noctilio* populations in exotic pine plantations: critical issues explaining invasion success and damage levels in South America. *J. Pest Sci.* 92:131-142

44. Costanza KKL, Livingston WH, Kashian DM, Slesak RA, Tardif JC, et al. 2017. The Precarious State of a Cultural Keystone Species: Tribal and Biological Assessments of the Role and Future of Black Ash. *J. For.* 115(5):435–446

45. Cox M, Arnold G, Tomás SV. 2010. A review of design principles for community-based natural resource management. *Ecol. Soc.* 15

46. Coutiho TA, Wingfield MJ, Alfenas AC, Crous PW. 1988. Eucalyptus rust: A disease with the the potential for serious international implications. *Plant Dis.* 82:819-825

47. Dahlsten DL, Mills NJ. 1999. Biological control of forest insects. In *Handbook of biological control*, ed. TS Bellows, TW Fisher, LE Caltagirone, DL Dahlsten, G Gordh, CB Huffaker, pp 761–788. San Diego, CA: Academic Press

48. DeRose RJ, Long JN. 2014. Resistance and resilience: a conceptual framework for silviculture. Forest Science 60(6):1205-12

49. Diagne C, Leroy B, Vaissière A-C, Gozlan RE, Roiz D, et al. 2021. High and rising economic costs of biological invasions worldwide. *Nature* 592:517-576

50. Dickson B, Cooney RE. 2012. Biodiversity and the precautionary principle: risk, uncertainty and practice in conservation and sustainable use. London, U.K.: Routledge

51. Dort EN, Tanguay P, Hamelin RC. 2020. CRISPR/Cas9 Gene Editing: An Unexplored

Frontier for Forest Pathology. *Front. Plant Sci.* 11:1126

52. Drever CR, Peterson G, Messier C, Bergeron Y, Flannigan M. 2006. Can forest management based on natural disturbances maintain ecological resilience? *Can. J. For. Res.* 36:2285–2299

53. Dudley N, Jones T, Gerber K, Ross-Davis AL, Sniezko RA, et al. 2020. Establishment of a Genetically Diverse, Disease-Resistant *Acacia koa* A. Gray Seed Orchard in Kokee, Kauai: Early Growth, Form, and Survival. *Forests* 11:1276

54. Dukes JS, Pontius J, Orwig D, Garnas JR, Rodgers VL, et al. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Can. J. For. Res.* 39:231–248

55. Early R, Bradley BA, Dukes JS, Lawler JJ, Olden JD, et al. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. *Nat. Commun.* 7:1–9

56. Elkinton JS, Boettner GH, Broadley HJ. 2021. Successful biological control of winter moth, *Operophtera brumata*, in the northeastern United States. *Ecol. Appl.* doi:10.1002/eap.2326

57. Epanchin-Niell R, McAusland C, Liebhold A, Mwebaze P, Springborn MR. 2021. Biological invasions and international trade: Managing a moving target. *Rev. Environ. Econ. Pol*. 15(1):180-90

58. Eschen R, Britton K, Brockerhoff E, Burgess T, Dalley V, et al. 2015. International variation in phytosanitary legislation and regulations governing importation of plants for

planting. *Environ. Sci. Pol.* 51:228-237

59. Eschen R, Roques A, Santini A. 2015b. Taxonomic dissimilarity in patterns of interception and establishment of alien arthropods, nematodes and pathogens affecting woody plants in Europe. *Divers. Distrib.* 21:36–45. https://doi.org/10.1111/ddi.12267
60. Eschen R, O'Hanlon R, Santini A, Vannini A, Roques A, et al. 2019. Safeguarding global plant health: the rise of sentinels. *J. Pest. Sci.* 92:29-36
61. Escobedo FJ, Adams DC, Timilsina N. 2015. Urban forest structure effects on property value. *Ecosyst. Serv.* 12:209-217
62. Evans EA, Crane J, Hodges A, Osborne JL. 2010. Potential economic impact of laurel wilt disease on the Florida avocado industry. *HortTechnology* 20:234–238
63. Evans KJ, Scott JB, Barry KM. 2020. Pathogen Incursions--Integrating Technical Expertise in a Socio-Political Context. *Plant Disease* 104:3097-3109. https://doi.org/10.1094/PDIS-04-20-0812-FE
64. Ewing CJ, Hausman CE, Pogacnik J, Slot J, Bonello P. 2019. Beech leaf disease: An emerging forest epidemic. *Forest Pathology* 49
65. Faier L, Group MWR. 2011. Fungi, trees, people, nematodes, beetles, and weather: ecologies of vulnerability and ecologies of negotiation in matsutake commodity exchange. *Environ. Plan. A Econ. Sp.* 43:1079–1097
66. Farjon A. 2013. *Chamaecyparis lawsoniana*. The IUCN Red List of Threatened Species 2013: e.T34004A2840024. Report. https://dx.doi.org/10.2305/IUCN. UK.2013-

1.RLTS.T34004A2840024.en

67. Federman S, Zankowski P. 2020. Strategic science planning for responsible stewardship and plant protection at the US Department of Agriculture. *Plants, People, Planet* 2:53– 56. https://doi.org/10.1002/ppp3.10075
68. Fei S, Morin RS, Oswalt CM, Liebhold AM. 2019. Biomass losses resulting from insect and disease invasions in US forests. *Proc. Nat. A. Sci.* 116:17371–17376
69. Fielding NJ, Evans HF. 1997. Biological control of *Dendroctonus micans* (Scolytidae) in Great Britain. *Biocontrol News and Information* 18(2)
70. Fitzsimmons S, Gurney K, White W, McCune K. 2012. The chapter breeding program of the American Chestnut Foundation. In *Proceedings of the fourth international workshop on the genetics of host-parasite interactions in forestry: Disease and insect resistance in forest trees, Gen. Tech. Rep. PSW-GTR-240*, tech. coords. RA Sniezko, AD Yanchuk, JT Kliejunas, KM Palmieri, JM Alexander, SJ Frankel, p. 303. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture
71. Fleischman F, Basant S, Chhatre A, Coleman EA, Fisher HW, et al. 2020. Pitfalls of Tree Planting Show Why We Need People-Centered Natural Climate Solutions. BioScience 70(11):947–950
72. Food and Angricultural Organization of the United Nations (FAO). 2009. Global review of forest pests and diseases. FAO Forestry Paper 156. Report. https://www.fao.org/3/i0640e/i0640e00.htm

73. Fox T, Lyons A, Miller DA, Rakestraw J, Rojas J, et al. 2019. Forest Health Alliance: An Industry Perspective. *The Forestry Source* 24:16
74. Fraedrich SW, Harrington TC, Bates CA, Johnson J, Reid LS, et al. 2011. Susceptibility to laurel wilt and disease incidence in two rare plant species, pondberry and pondspice. *Plant Dis.* 95:1056–1062
75. Gallagher PB. 2014. Redbay Trees are Dying. *The Seminole Tribune*. February 25, 2014. https://seminoletribune.org/redbay-trees-are-dying/
76. Gallagher PB. 2015. Much Research, Few Answers As Laurel Wilt Disease Spreads. *The Seminole Tribune*. July 1, 2015. https://seminoletribune.org/much-research-few-answers-as-laurel-wilt-disease-spreads/
77. Gandhi KJK, Campbell F, Abrams J. 2019. Current status of forest health policy in the United States. *Insects* 10:106
78. Gandhi KJK, Herms DA. 2010. North American arthropods at risk due to widespread *Fraxinus mortality* caused by the alien emerald ash borer. *Biolog. Invas.* 12:1839–1846
79. Gandhi KJK, Klepzig KD, Dean JD, Hunter E, Liebhold A, et al. 2021. The Pine Pandemic Preparedness Plan (P4): One Proactive Approach to Combating Invasive Pests and Pathogens on Southern Pines. *The Forestry Source*, November Edition, Page 9
80. Gao L, Li Y, Wang ZX, Zhao J, Hulcr J, et al. 2021. Biology and associated fungi of an emerging bark beetle pest, the sweetgum inscriber *Acanthotomicus suncei* (Coleoptera: Curculionidae). *J. Appl. Entomol.* 145(6):508-17

81. Garzon ARG, Bettinger P, Siry J, Abrams J, Cieszewski C, et al. 2020. A comparative analysis of five forest certification programs. *Forests* 11

82. Gavin MC, McCarter J, Berkes F, Mead ATP, Sterling EJ, et al. 2018. Effective biodiversity conservation requires dynamic, pluralistic, partnership-based approaches. *Sustainability* 10:1846. https://doi.org/10.3390/su10061846

83. Gherghina ȘC, Simionescu LN, Hudea OS. 2019. Exploring foreign direct investment--economic growth nexus—Empirical evidence from central and eastern European countries. *Sustainability* 11:5421

84. Gilbert GS, Magarey R, Suiter K, Webb CO. 2012. Evolutionary tools for phytosanitary risk analysis: phylogenetic signal as a predictor of host range of plant pests and pathogens. *Evol. Appl.* 5:869-878

85. Gilbert GS, Webb CO. 2007. Phylogenetic signal in plant pathogen–host range. *Proc. Nat. A. Sci.* 104:4979-4983

86. Glen M, Alfenas AC, Zauza EAV, Wingfield MJ, Mohammed C. 2007. *Puccinia psidii:* A threat to the Australian environment and economy- a review. *Austral. Plant Path.* 36:1-16

87. Gomez DF, Adams DC, Cossio RE, de Grammont PC, Messina WA, et al. 2020. Peering into the Cuba phytosanitary black box: An institutional and policy analysis. *PloS One* 15:e0239808

88. Gonthier P, Garbelotto M. 2013. Reducing the threat of emerging infectious diseases of forest trees—Mini Review. *CAB Reviews: Perspect. Ag. Vet. Sci. Nutr. Nat. Res.* 8

89. Gougherty AV, Jonathan DT. 2021. Towards a phylogenetic ecology of plant pests and pathogens. *Philos. T. T. Soc. B* 376:20200359
90. Graham S, Metcalf AL, Gill N, Niemiec R, Moreno C, et al. 2019. Opportunities for better use of collective action theory in research and governance for invasive species management. *Conserv. Biol.* 33:275–287
91. Gramling JM. 2010. Potential effects of laurel wilt on the flora of North America. *Southeast. Nat.* 9:827–836
92. Graziosi I, Tembo M, Kuate J, Muchugi A. 2019. Pests and diseases of trees in Africa: A growing continental emergency. *Plants, People, Planet* 2(1):14-28
93. Green S, Elliot M, Armstrong A, Hendry SJ. 2015. *Phytophthora austrocedrae* emerges as a serious threat to juniper (*Juniperus communis*) in Britain. *Plant Pathol.* 64:456–466
94. Guo Q, Fei S, Potter KM, Liebhold AM, Wen J. 2019. Tree diversity regulates forest pest invasion. *Proc. Nat. A. Sci.* 116:7382–7386
95. Haack RA, Britton KO, Brockerhoff EG, Cavey JF, Garrett LJ, et al. 2014. Effectiveness of the International Phytosanitary Standard ISPM No. 15 on reducing wood borer infestation rates in wood packaging material entering the United States. *PLoS One* 9:e96611
96. Hadziabdic D, Bonello P, Hamelin RC, Juzwik J, Moltzan B, et al. 2021. The future of forest pathology in North America. *Front. For. Glob. Chg*. 4:737445
97. Hajek AE, Eilenberg J. 2018. Natural Enemies: An Introduction to Biological Control. Cambridge, UK: Cambridge Univ. Press. 2nd Ed.

98. Hajek AE, Gardescu S, Delalibera Jr I. 2020. Classical biological control of insects and mites: A comprehensive list of pathogen and nematode introductions. Online Data. https://ecommons.cornell.edu/xmlui/handle/1813/69611

99. Halpern CB. 1988. Early successional pathways and the resistance and resilience of forest communities. *Ecology* 69(6):1703-15

100. Hamelin RC, Roe AD. 2020. Genomic biosurveillance of forest invasive alien enemies: A story written in code. *Evol. Appl.* 13(1)

101. Hantula J, Müller MM, Uusivuori J. 2014. International plant trade associated risks: Laissez-faire or novel solutions. *Environ. Sci. Pol.* 37:158–160

102. Heger T, Jeschke JM. 2014. The enemy release hypothesis as a hierarchy of hypotheses. *Oikos* 123:741–750

103. Hopper KR, Roush RT, Powell W. 1993. Managing the genetics of biological control introductions. *Annu. Rev. Entomol.* 38:27-51

104. Howlett M, Ramesh M, Perl A. 2009. Studying public policy: Principles and Processes. Oxford, UK: Oxford University Press

105. Hufbauer RA, Roderick GK. 2005. Microevolution in biological control: mechanisms, patterns, and processes. *Biol. Control* 35:227-239

106. Hughes MA, Inch SA, Ploetz RC, Er HL, van Bruggen AHC, Smith JA. 2015. Responses of swamp bay, *Persea palustris*, and avocado, *Persea americana*, to various concentrations of the laurel wilt pathogen, *Raffaelea lauricola*. *Forest Pathol.* 45:111–119

107. Hultberg T, Sandström J, Felton A, Öhman K, Rönnberg J, et al. 2020. Ash dieback risks an extinction cascade. *Biol. Conserv.* 244:108516

108. Hurley BP, Slippers B, Wingfield MJ. 2007. A comparison of control results for the alien invasive woodwasp, *Sirex noctilio*, in the southern hemisphere. *Ag. For. Entomol.* 9:159–171

109. Ingwell LL, Preisser EL. 2011. Using citizen science programs to identify host resistance in pest-invaded forests. *Conserv. Biol.* 25(1):182-8

110. Jactel H, Birgersson G, Andersson S, Schlyter F. 2011. Non-host volatiles mediate associational resistance to the pine processionary moth. *Oecologia* 166:703–711

111. Jactel H, Desprez-Loustau M-L, Battisti A, Brockerhoff E, Santini A, et al. 2020. Pathologists and entomologists must join forces against forest pest and pathogen invasions. *NeoBiota* 58:107

112. Jactel H, Moreira X, Castagneyrol B. 2021. Tree Diversity and Forest Resistance to Insect Pests: Patterns, Mechanisms, and Prospects. *Annu. Rev. Entomol.* 66:277–296

113. Jepson PR, Arakelyan I. 2017. Developing publicly acceptable tree health policy: public perceptions of tree-breeding solutions to ash dieback among interested publics in the UK. *For. Pol. Econ.* 80:167–177

114. Jerin T, Phillips J. 2020. Biogeomorphic keystones and equivalents: examples from a bedrock stream. *Earth Surf. Proc. Land.* 45(8):1877-1894

115. Johnson TD, Lelito, JP, Pfammatter JA, Raffa KF. 2016. Evaluation of tree mortality and

parasitoid recoveries on the contiguous western invasion edge of emerald ash borer. *Ag. For. Entomol.* 18:327-339

116. Jones M, Mautner A, Luenco S, Bismarck A, John S. 2020. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Mat. Des.* 187
117. Jules ES, Kauffman MJ, Ritts WD, Carroll AL. 2002. Spread of an invasive pathogen over a variable landscape: a nonnative root rot on port orford cedar. *Ecology* 83:3167–3181
118. Jung T, Jung MH, Webber JF, Kageyama K, Hieno A, et al. 2021. The Destructive Tree Pathogen *Phytophthora ramorum* Originates from the Laurosilva Forests of East Asia. *J. Fungi* 7:226
119. Kemler M, Garnas J, Wingfield MJ, Gryzenhout M, Pillay K-A, Slippers B. 2013. Iron torrent PGM as a tool for fungal community analysis: A case study in *Eucalyptus grandis* reveals high taxonomic diversity. *PloS One* 8: e81718. https://doi.org/10.1371/journal.pone.0081718
120. Kenis M, Hurley BP, Hajek AE, Cock MJ. 2017. Classical biological control of insect pests of trees: facts and figures. *Biol. Invas.* 19(11):3401-3417
121. Khadka A. 2017. Assessment of the perceived effects and management challenges of *Mikania micrantha* invasion in Chitwan National Park buffer zone community forest, Nepal. *Heliyon* 3(4):e00289
122. Klapwijk MJ, Hopkins AJM, Eriksson L, Pettersson M, Schroeder M, et al. 2016. Reducing the risk of invasive forest pests and pathogens: Combining legislation, targeted management

and public awareness. *AmBio* 45:223–234

123. Kline N, Navarro S, LeBoldus J. 2020. Using citizen science and outreach education to reduce the risk of *Phytophthora ramorum* spread in Oregon forests. In *Proceedings of the seventh sudden oak death science and management symposium: healthy plants in a world with Phytophthora, Gen. Tech. Rep. PSW-GTR-268,* tech. coords. SJ Frankel, JA Alexander. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture

124. Klooster WS, Gandhi KJK, Long LC, Perry KI, Rice KB, Herms DA. 2018. Ecological impacts of emerald ash borer in forests at the epicenter of the invasion in North America. *Forests* 9:250

125. Koch JL, Carey DW, Mason ME, Poland TM, Knight KS. 2015. Intraspecific variation in *Fraxinus pennsylvanica* responses to emerald ash borer (*Agrilus planipennis*). *New Forests* 46:995-1011

126. Kolařík M, Freeland E, Utley C, Tisserat N. 2011. *Geosmithia morbida* sp. nov., a new phytopathogenic species living in symbiosis with the walnut twig beetle (*Pityophthorus juglandis*) on *Juglans* in USA. *Mycologia* 103

127. Kreye M, Adams D, Escobedo F. 2014. The Value of Forest Conservation for Water Quality Protection. *Forests* 5:862–884

128. Krause SL, Raffa KF. 1996. Defoliation tolerance affects the spatial and temporal distributions of larch sawfly and natural enemy populations. *Ecolog. Entomol.* 21:101-111

129. Kumar P. 2010. The economics of ecosystems and biodiversity: ecological and economic foundations. UNEP/Earthprint

130. Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, et al. 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452:987–990

131. La Y-J. 2009. Korean successes in controlling blister rust of Korean pine. In *Breeding and Genetic Resources of Five-Needle Pines Conference, Yangyang, Republic of Korea, September 22-26, 2008*, ed. D Noshad, E Noh, J King, R Sniezko, pp. 1-9

132. Laffoley D, Baxter JM, Amon DJ, Currie DEJ, Downs CA, et al. 2020. Eight urgent, fundamental and simultaneous steps needed to restore ocean health, and the consequences for humanity and the planet of inaction or delay. *Aquatic Conserv.* 30:194–208

133. Lake PS. 2013. Resistance, resilience and restoration. *Ecol. Manag. Rest.* 14(1):20-4

134. Laursen B. 2018. What is collaborative, interdisciplinary reasoning? The heart of interdisciplinary team science. *Informing Science: The International Journal of an Emerging Transdiscipline* 21:075-106

135. Lee DJ, Adams DC, Kim CS. 2009. Managing invasive plants on public conservation forestlands: Application of a bio-economic model. *For. Pol. Econ.* 11(4):237-243

136. Lehtijärvi A, Aday Kaya AG, Woodward S, Jung T, Doğmuş Lehtijärvi HT. 2017. Oomycota species associated with deciduous and coniferous seedlings in forest tree nurseries of Western Turkey. *Forest Pathol.* 47(5):e12363

137. Lehtijärvi A, Oskay F, Dogmus Lehtijärvi HT, Aday Kaya AG, Pecori F, et al. 2018.

Ceratocystis platani is killing plane trees in Istanbul (Turkey). *Forest Pathol.* 48:e12375

138. Leung B, Springborn MR, Turner JA, Brockerhoff EG. 2014. Pathway-level risk analysis: the net present value of an invasive species policy in the US. *Front. Ecol. Environ.* 12:273-279

139. Liebhold AM, Brockerhoff EG, Garrett LJ, Parke JL, Britton KO. 2012. Live plant imports: the major pathway for forest insect and pathogen invasions of the US. *Front. Ecol. Environ.* 10:135–143

140. Liebhold AM, Brockerhoff EG, Kalisz S, Nuñez MA, Wardle DA, Wingfield MJ. 2017. Biological invasions in forest ecosystems. *Biol. Invas.* 19:3437–3458

141. Liebhold AM, Kean JM. 2019. Eradication and containment of non-native forest insects: successes and failures. *J. Pest Sci.* 92:83–91

142. Liebhold AM, MacDonald WL, Bergdahl D, Mastro VC. 1995. Invasion by exotic forest pests: a threat to forest ecosystems. *Forest Sci.* 41:a0001--z0001

143. Loo JA. 2009. Ecological impacts of non-indigenous invasive fungi as forest pathogens. *Biol. Invas.* 11(1):81-96

144. Lovett GM, Canham CD, Arthur MA, Weathers KC, Fitzhugh RD. 2006. Forest Ecosystem Responses to Exotic Pests and Pathogens in Eastern North America. *BioSci.* 56:395–405

145. Lovett G, Weiss M, Lambert KF. 2019. Preventing the importation of invasive forest pests through Tree-SMART Trade. Entomological Society of America Online, August, 2019. https://eco.confex.com/eco/2020/meetingapp.cgi/Paper/86805

146. Lovett GM, Weiss M, Liebhold AM, Holmes TP, Leung B, et al. 2016. Nonnative forest insects and pathogens in the United States: Impacts and policy options. *Ecol. Appl.* 26:1437–1455.

147. Loyd AL, Chase KD, Nielson A, Hoover N, Dreaden TJ, et al. 2020. First Report of Laurel Wilt Caused by *Raffaelea lauricola* on *Sassafras albidum* in Tennessee and Kentucky. *Plant Dis.* 104:567

148. Luchi N, Ioos R, Santini A. 2020. Fast and reliable molecular methods to detect fungal pathogens in woody plants. *Appl. Microbiol. Biotech.* 104:2453-2468

149. Lutts RH. 2004. Like manna from God: The American chestnut trade in southwestern Virginia. *Environ. Hist.* 9:497–525

150. MacQuarrie CJ, Lyons DB, Seehausen ML, Smith SM. 2016. A history of biological control in Canadian forests, 1882–2014. *Can. Entomol.* 148(S1):S239-69

151. Maloy OC. 1997. White pine blister rust control in North America: a case history. *Ann. Rev. Phytopathol.* 35:87–109

152. Mansfield S, McNeill MR, Aalders LT, Bell NL, Kean JM, et al. 2019. The value of sentinel plants for risk assessment and surveillance to support biosecurity. *NeoBiota* 48:1

153. Marini L, Ayres MP, Jactel H. 2022. Impact of Stand and Landscape Management on Forest Pest Damage. *Annu. Rev. Entomol*. 67:181-99

154. Martinez D, Duran EM, Bauer N. 2020. Saving ʻŌhiʻa: A Case Study on the Influence of Human Behavior on Ecological Degradation Through an Examination of Rapid ʻŌhiʻa

Death and Its Impacts on the Hawaiian Islands. *Case Studies Environ.* 4(1)

155. McDonald RI, Kroeger T, Zhang P, Hamel P. 2020. The value of US urban tree cover for reducing heat-related health impacts and electricity consumption. *Ecosystems* 23(1):137-150
156. McRoberts N, Thomas CS, Brown JK, Nutter FW, Stack JP, Martyn RD. 2016. The evolution of a process for selecting and prioritizing plant diseases for recovery plans. *Plant Dis.* 100(4):665-71
157. Meldrum JR, Champ PA, Bond CA. 2011. Valuing the forest for the trees: Willingness to pay for white pine blister rust management. In *The future of high-elevation, five-needle white pines in Western North America: Proceedings of the High Five Symposium, 28-30 June 2010, Missoula, MT Gen. Tech. Rep. RMRS-P-63*, ed. RE Keane, DF Tomback, MP Murray, CM Smith, p. 226-234. Fort Collins, CO: Rocky Mountain Research Station, Forest Service, US Department of Agriculture
158. Migliorini D, Ghelardini L, Luchi N, Capretti P, Onorari M, Santini M. 2019. Temporal petterns of airborne *Phytophthora* spp. in a woody plant nursery area detected using real-time PCR. *Aerobiologia* 35:201-214
159. Moore M, Juzwik J, Miller F, Roberts L, Ginzel, MD. 2019. Detection of *Geosmithia morbida* on numerous insect species in four eastern states. *Plant Health Prog.* 20:133-139
160. Mota M, Vieira, P, Eds. 2008. Pine Wilt Disease: A Worldwide Threat to Forest Ecosystems. Springer
161. Munck IA, Bonello P. 2018. Modern approaches for early detection of forest pathogens are

sorely needed in the United States. *For. Pathol.* 48:e12445

162. National Aeronautics and Space Administration (NASA). 2012. Seeing Forests for the Trees and Carbon: Mapping the World's Forests in Three Dimensions. Report. https://earthobservatory.nasa.gov/features/ForestCarbon/page1.php

163. National Academy of Sciences Engineering and Medicine. 2019. Forest health and biotechnology: Possibilities and considerations. Washington, DC: The National Academies Press. https://doi.org/10.17226/25221

164. National Research Council. 2005. Facilitating interdisciplinary research. Washington, DC: National Academies Press

165. Nelson CD, Koch JL. 2017. Institute of forest tree breeding: Improvement and gene conservation of iconic tree species in the 21st century. In *Gene conservation of tree species—banking on the future. Proceedings of a workshop, Gen. Tech. Rep. PNW-GTR-963*, tech. coords. RA Sniezko, G Man, V Hipkins, K Woeste, D Gwaze, JT Kliejunas, BA McTeague. Portland, OR: Pacific Northwest Research Station, Forest Service, US Department of Agriculture

166. Nerfa L, Rhemtulla JM, Zerriffi H. 2020. Forest dependence is more than forest income: Development of a new index of forest product collection and livelihood resources. *World Devel*, 125:104689

167. Newhouse AE, Polin-McGuigan LD, Baier KA, Valletta KER, Rottmann WH, et al. 2014. Transgenic American chestnuts show enhanced blight resistance and transmit the trait to T1

progeny. *Plant Sci.* 228:88–97

168. Olatinwo RO, Fraedrich SW, Mayfield AE. 2021. Laurel Wilt: Current and Potential Impacts and Possibilities for Prevention and Management. *Forests* 12(2):181
169. Ormsby M, Brenton-Rule E. 2017. A review of global instruments to combat invasive alien species in forestry. *Biolog. Invas.* 19:3355–3364. https://doi.org/10.1007/s10530-017-1426-0
170. Ostrom E. 1990. Governing the commons: The evolution of institutions for collective action. Cambridge, U.K.: Cambridge University Press
171. Ostrom E. 2010. A multi-scale approach to coping with climate change and other collective action problems. *Solutions* 1:27–36
172. Paap T, Burgess TI, Wingfield MJ. 2017. Urban trees: Bridgeheads for forest pest invasions and sentinels for early detection. *Biolog. Invas.* 19:3515-3526
173. Paap T, Wingfield MJ, Burgess TI, Hulbert JM, Santini A. 2020. Harmonising the fields of invasion science and forest pathology. *NeoBiota* 62:301
174. Paap T, Wingfield MJ, Burgess TI, Wilson JRU, Richardson DM, Santini A. Invasion frameworks: a forest pathogen perspective. *Curr. For. Rep*. In press
175. Pautasso M, Aas G, Queloz V, Holdenrieder O. 2013. European ash (*Fraxinus excelsior*) dieback – A conservation biology challenge. *Biol. Conserv.* 158:37-49
176. Pawson SM, Sullivan JJ, Grant A. 2020. Expanding general surveillance of invasive species by integrating citizens as both observers and identifiers. *J. Pest Sci.* 93:1155–1166

177. Pike CC, Koch J, Nelson CD. 2021. Breeding for Resistance to Tree Pests: Successes, Challenges, and a Guide to the Future. *J. Forest.* 119:96–105

178. Ploetz RC, Hulcr J, Wingfield MJ, de Beer ZW. 2013. Destructive Tree Diseases Associated with Ambrosia and Bark Beetles: Black Swan Events in Tree Pathology? *Plant Dis.* 97:856–872

179. Potter KM, Escanferla ME, Jetton RM, Man G. 2019. Important insect and disease threats to United States tree species and geographic patterns of their potential impacts. *Forests* 10:304

180. Powell WA, Newhouse AE, Coffey V. 2019. Developing blight-tolerant American chestnut trees. *CSH Perspect. Biol.* 11:a034587

181. Prospero S, Botella L, Santini A, Robin C, 2021. Biological control of emerging forest diseases: How can we move from dreams to reality? *For. Ecol. Manag.* 496:119377. https://doi.org/10.1016/j.foreco.2021.119377

182. Pureswaran DS, Roques A, Battisti A. 2018. Forest insects and climate change. *Curr. For. Reports* 4:35–50

183. Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, et al. 2020. Scientists' warning on invasive alien species. *Biol. Rev. Cambridge Phil. Soc.* 95(6):1511-1534

184. Quirion B, Domke GM, Walters BF, Lovett GM, Fargione J, et al. 2021. Insect and disease disturbances correlate with reduced carbon sequestration capacity in forests of the contiguous United States. *Front. For. Glob. Chg.* 4:143. https://doi.org/10.3389/ffgc.2021.716582

185. Rabaglia R, Cognato AI, Hoebeke ER, Johnson CW, LaBonte JR, et al. 2019 Early Detection and Rapid Response: A 10-Year Summary of the USDA Forest Service Program of Surveillance for Non-Native Bark and Ambrosia Beetles. *American Entomologist* 65(1):29-42

186. Ramsfield TD, Bentz BJ, Faccoli M, Jactel H, Brockerhoff EG. 2016. Forest health in a changing world: effects of globalization and climate change on forest insect and pathogen impacts. *Forestry* 89:245–252

187. Razafindratsima OH, Kamoto JFM, Sills EO, Mutta DN, Song C, et al. 2021. Reviewing the evidence on the roles of forests and tree-based systems in poverty dynamics. *Forest Pol. Econ.* 131:102576. https://doi.org/https://doi.org/10.1016/j.forpol.2021.102576

188. Redmond T, Nasir MA. 2020. Role of natural resource abundance, international trade and financial development in the economic development of selected countries. *Res. Pol.* 66:101591

189. Reyes-García V, Fernández-Llamazares Á, McElwee P, Molnár Z, Öllerer K, et al. 2019. The contributions of Indigenous Peoples and local communities to ecological restoration. *Rest. Ecol.* 27(1):3-8

190. Robertson PA, Mill A, Novoa A, Jeschke JM, Essl F, et al. 2020. A proposed unified framework to describe the management of biological invasions. *Biol. Invas.* 22:2633–2645

191. Rosenbaum WA. 2020. Environmental Politics and Policy. Washington, DC: CQ Press, 11th Edition

192. Roura-Pascual N, Leung B, Rabitsch W. et al. 2020. Alternative futures for global biological invasions. *Sustain. Sci.* 16:1637–1650. https://doi.org/10.1007/s11625-021-00963-6

193. Roy BA, Alexander HM, Davidson J, Campbell FT, Burdon, JJ, et al. 2014. Increasing forest loss worldwide from invasive pests requires new trade regulations. *Front. Ecol. Environ.* 12(8):457-465

194. Russell JC, Blackburn TM. 2017. The Rise of Invasive Species Denialism. *Trends Ecol. Evol.* 32:3–6

195. Ryan RB. 1997. Before and After Evaluation of Biological Control of the Larch Casebearer (Lepidoptera: Coleophoridae) in the Blue Mountains of Oregon and Washington, 1972–1995. *Environ. Entomol.* 26(3):703-715

196. Santini A, Ghelardini L, De Pace C, Desprez-Loustau M-L, Capretti P, et al. 2013. Biogeographical patterns and determinants of invasion by forest pathogens in Europe. *New Phytol.* 197:238–250

197. Santini A, Liebhold A, Migliorini D, Woodward S. 2018. Tracing the role of human civilization in the globalization of plant pathogens. *The ISME Journal* 12:647–652

198. Schultz AN, Lucardi RD, Marsico TD. 2019. Successful Invasions and Failed Biocontrol: The Role of Antagonistic Species Interactions. *BioScience* 69(9):711-714. https://doi.org/10.1093/biosci/biz075

199. Seebens H, Essl F, Dawson W, Fuentes N, Moser D, et al. 2015. Global trade will accelerate plant invasions in emerging economies under climate change. *Glob. Chg. Biol.* 21:4128-

4140

200. Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, et al. 2020. Projecting the continental accumulation of alien species through to 2050. *Glob. Chg. Biol*. 27:970-982

201. Seebens H, Blackburn T, Dyer E, Genovesi P, Hulme PA, et al. 2017. No saturation in the accumulation of alien species worldwide. *Nature Comm.* 8:14435. https://doi.org/10.1038/ncomms14435

202. Shin SC. 2008. Pine wilt disease in Korea. In *Pine wilt disease: A worldwide threat to forest ecosystems*, eds. MM Mota, PR Vieira. Springer

203. Showalter DN, Raffa KF, Sniezko RA, Herms DA, Liebhold AM, et al. 2018. Strategic development of tree resistance against forest pathogen and insect invasions in defense-free space. *Front Ecol. Evol.* 6:124

204. Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, et al. 2013. Impacts of biological invasions: what's what and the way forward. *Trends Ecol. Evol.* 28(1):58-66

205. Slippers B. Wingfield MJ. 2007. Botryosphaeriaceae as endophytes and latent pathogens of woody plants: diversity, ecology and impact. *Fungal Biol. Rev.* 21:90-106

206. Smallwood CJ, Ethington M, Ginzel M. Managing Thousand Cankers Disease in High-value Plantings of Black Walnut (Fagales: Juglandaceae) in Washington State. *J. IPM.* In press

207. Sniezko RA, Johnson JS, Reeser P, Kegley A, Hansen EM, et al. 2020. Genetic resistance to *Phytophthora lateralis* in Port-Orford-cedar (*Chamaecyparis lawsoniana*) – Basic building

blocks for a resistance program. *Plants, People, Planet* 2:69–83

208. Sniezko RA, Johnson JS, Savin DP. 2020. Assessing the durability, stability, and usability of genetic resistance to a non-native fungal pathogen in two pine species. *Plants, People, Planet* 2:57–68

209. Sniezko RA, Koch J. 2017. Breeding trees resistant to insects and diseases: putting theory into application. *Biol. Invas.* 19:3377–3400

210. Sniezko RA, Liu JJ. 2021. Prospects for developing durable resistance in populations of forest trees. *N. For.* https://doi.org/10.1007/s11056-021-09898-3

211. Solano A, Rodriguez SL, Coyle DR. 2020. The Nature Conservancy's Don't Move Firewood campaign: An analysis of the 2005–2016 survey data. Online. http://www.dontmovefirewood.org/wp-content/uploads/2020/07/Solano-Rodriguez-and-Coyle-DMF-Report-for-2005-2016-Survey-Data_2.pdf

212. Soulioti N, Tsopelas P, Woodward S. 2018. *Ceratocystis platani*: an invasive fungal pathogen threatening natural populations of Oriental Plane in Greece. Presented at ISFOR, October 2017, Isparta, Turkey. doi: 10.13140/RG.2.2.26033.89447.

213. Specter SP. 2019. Seven alternative pallets for greener operations: Alternative materials and hybrid combinations in pallets target improved sustainability. *Modern Materials Handling*. June 11, 2019. Article. https://www.mmh.com/article/seven_alternative_pallets_for_greener_operations.

214. Spence N, Hill L, Morris J. 2020. How the global threat of pests and diseases impacts

plants, people, and the planet. *Plants, People, Planet* 2:5–13

215. Susaeta A, Soto JR, Adams DC, Hulcr J. 2017. Expected Timber-Based Economic Impacts of a Wood-Boring Beetle (*Acanthotomicus* sp.) That Kills American Sweetgum. *J. Econ. Entomol*. 110(4):1942-1945. doi: 10.1093/jee/tox165
216. Theoharides KA, Dukes JS. 2007. Plant invasion across space and time: factors affecting nonindigenous species success during four stages of invasion. *New Phytol.* 176:256-273
217. Tobin PC, Kean JM, Suckling DM, McCullough DG, Herms DA, Stringer LD. 2014. Determinants of successful arthropod eradication programs. *Biol. Invas.* 16:401–414
218. Tsing AL. 2015. The Mushroom at the End of the World. Princeton, NJ: Princeton University Press
219. Tsopelas P, Santini A, Wingfield M, DeBeer W. 2017. Canker stain: A lethal disease destroying iconic plane trees. *Plant Dis.* 101:645-658. http://dx.doi.org/10.1094/PDIS-09-16-1235-FE
220. Tucker AW. 1983. A Two-Person Dilemma: The Prisoner's Dilemma. *The Two-Year College Mathematics Journal* 14:228
221. Turner J, Jennings P, Humphries G, Parker S, McDonough S, et al. 2007. Natural Outbreaks of *Phytophthora ramorum* in the U.K.—Current Status and Monitoring Update. In *Proceedings of the Sudden Oak Death Third Science Symposium, Gen. Tech. Rep. PSW-GTR-214,* tech. coords. SJ Frankel, JT Kliejunas, KM Palmieri. Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

https://www.fs.fed.us/psw/publications/documents/psw_gtr214/psw_gtr214_043-048_turner.pdf

222. Turner RM, Brockerhoff, EG, Bertelmeier C, Blake RE, Caton B, et al. 2021. Worldwide border inspections provide a window into human-mediated global insect movement. *Ecol. Appl.* 31(7):e02412

223. Ugawa S, Fukuda K. 2008. Effect of aerial spraying of insecticide as a control measure for pine wilt disease. In *Pine wilt disease: A worldwide threat to forest ecosystems*, eds. MM Mota, PR Vieira. Springer

224. Van Driesche RG, Carruthers RI, Center T, Hoddle MS, Hough-Goldstein J, et al. 2010. Classical biological control for the protection of natural ecosystems. *Biol. Control* 54

225. Vélez ML, La Manna L, Tarabini M, Gomez F, Elliott M, et al. 2020. *Phytophthora austrocedri* in Argentina and Co-Inhabiting *Phytophthoras*: Roles of Anthropogenic and Abiotic Factors in Species Distribution and Diversity. *Forests* 11:1223

226. Villari C, Dowkiw A, Enderle R, Ghasemkhani M, Kirisits T, et al. 2018. Advanced spectroscopy-based phenotyping offers a potential solution to the ash dieback epidemic. *Sci. Rep.* 8:17448

227. Ward SF, Aukema BH, Fei S, Liebhold AM. 2020. Warm temperatures increase population growth of a nonnative defoliator and inhibit demographic responses by parasitoids. *Ecology* 101(11):e03156

228. Wasielewski J. 2020. Laurel Wilt - A Disease Impacting Avocados. Report, University of

Florida Institute of Food and Agricultural Sciences Extension. https://sfyl.ifas.ufl.edu/miami-dade/agriculture/laurel-wilt---a-disease-impacting-avocados/

229. Westbrook JW, Holliday JA, Newhouse AE, Powell WA. 2020. A plan to diversify a transgenic blight-tolerant American chestnut population using citizen science. *Plants, People, Planet* 2:84–95

230. Westbrook JW, Holliday JA, Powell WA. 2020. Restoration of American Chestnut: a marriage of breeding and biotechnology. In *Proceedings of the Sixth International Workshop on the Genetics of Host-Parasite Interactions in Forestry—Tree Resistance to Insects and Diseases: Putting Promise into Practice, Gen. Tech. Rep. SRS-252,* tech. coords. DC Nelson, JL Koch, RA Sniezko. Asheville, NC: Southern Research Station, Forest Service, US Department of Agriculture

231. Wheeler NC, Steiner KC, Schlarbaum SE, Neale DB. 2015. The evolution of forest genetics and tree improvement research in the United States. *J. Forestry* 113(5):500-510. https://doi.org/10.5849/jof.14-120

232. Widianingsih NN, Theilade I, Pouliot M. 2016. Contribution of forest restoration to rural livelihoods and household income in Indonesia. *Sustainability* 8:835

233. Williams GM, Sniezko RA. 2021. A Sentinel Information Platform for North American Woody Flora: Leveraging Established Ex Situ Resources and Integration with Other Efforts. In *IUFRO Joint Meeting. Biological Invasions in Forests: Trade, Ecology, and Management, September 20-24, 2021*. Prague, Czech Republic.

234. Wilson EO. 2016. Half-earth: our planet's fight for life. Norton & Company

235. Wingfield MJ, Brockerhoff EG, Wingfield BD, Slippers B. 2015. Planted forest health: the need for a global strategy. *Science* 349:832–836

236. Wingfield MJ, Slippers B, Wingfield BD, Barnes I. 2017. The unified framework for biological invasions: A forest fungal pathogen perspective. *Biol. Invas.* 19:3201-3214.

237. Wittmann, ME, Chandra, S, Boyd, K, Jerde, CL. 2015. Implementing invasive species control: a case study of multi-jurisdictional coordination at Lake Tahoe, USA. *Manag. Biol. Invas.* 6(4):319–328

238. Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak NE, van Wilgen BW, et al. 2016. Confronting the wicked problem of managing biological invasions. *NeoBiota* 31:63–86

239. World Trade Organization (WTO). 2010. Sanitary and Phytosanitary Measures. The WTO Agreements Series. Book. https://www.wto.org/english/res_e/booksp_e/agrmntseries4_sps_e.pdf

240. World Trade Organization (WTO). 2021. Sanitary and Phytosanitary Measures. Website. https://www.wto.org/english/tratop_e/sps_e/sps_e.htm

241. Wu N, Zhang S, Li X, Cao Y, Liu X, et al. 2019. Fall webworm genomes yield insights into rapid adaptation of invasive species. *Nature Ecol. Evol.* 3:105–115

242. Xu F. 2008. Recent advances in the integrated management of the pine wood nematode in China. In *Pine Wilt Disease*, eds. BG Zha, K Futai, JR Sutherland, Y Takeuchi. Tokyo: Springer. https://doi.org/10.1007/978-4-431-75655-2_33

243. Yan Z, Sun J, Don O, Zhang Z. 2005. The red turpentine beetle, *Dendroctonus valens* LeConte (Scolytidae): an exotic invasive pest of pine in China. *Biodivers. Conserv*. 14:1735–1760

244. Zhang XY, Lu Q, Sniezko R, Song RQ, Man G. 2010. Blister rusts in China: hosts, pathogens, and management. *Forest Pathol*. 40:369-381

Annual Reviews Optional Elements

Reference annotations

11. Review and meta-analysis that identifies the most critical collective action principles in plant invasion dilemmas

18. Introduces concept of Centers for Forest Pest Control and Prevention

63. Considers socio-political dimensions of invasive plant pathogens and treats plant health as a common-pool resource

169. Good review of current instruments aimed at curbing forest invasive species and their history

170. Nobel-winning work on collective action to solve common pool resource social dilemmas in natural resources

193. Wake-up call linking invasions to trade, inadequacy of current policy and need for proactive approach

199. Identifies growing threat to biodiversity in emerging economies

209. Reviews practical considerations of implementing effective resistance breeding programs in forestry

214. Uses two case studies to put people first in telling the invasive forest pest narrative

238. Uses case studies to highlight how sociopolitical dimensions of invasions complicate and restrict solution space

Terms and Definitions

1. Common-pool resource

   A resource such as fisheries, air quality or forest health for which benefits, damages, and responsibility are shared among stakeholders

2. Prisoner's dilemma

   Two-choice, two-player, double-blind game in which cooperation carries the largest payout if mutual but the largest penalty if the other player defects

3. Collective action

   Action taken by multiple actors to achieve a common objective; also known as the solution to a social dilemma

4. Economic risk assessment

   The process of assessing risk based on probability, expected impact, and economic value of resources threatened by a biological threat

5. Biosecurity

   Protective measures taken to prevent the introduction of organisms that could threaten biological resources or people

6. Monitoring and surveillance

   The use of visual inspections, traps, remote sensing, molecular detection, and other technologies to detect pests

7. Early detection and rapid response

Effective monitoring and surveillance that leads to timely detection that ultimately triggers effective containment and eradication of invasive pest incursions

8. Sanitation

    A silvicultural pest management measure in which forest stand structure is augmented to impede pest spread and population growth

9. Salvage

    A silvicultural pest management measure aimed at the reduction of pest populations achieved by the removal of infested trees

10. Chemical suppression

    The application of chemicals, typically toxic insecticides, fungicides, etc. to deter, inhibit, or kill pests to reduce their populations and impact

11. Behavioral control

    Behavioral modification, typically achieved through the deployment of semio- (behaviorally active) chemicals, to attract, repel, or disrupt life-cycles of insects

12. Biological control

    The introduction, augmentation or conservation of predators, pathogens, and competitors to regulate pest populations in invaded ecosystems

13. Host resistance (general)

    Relating to a plant, relative minimization (quantitative) or absolute prevention (gene-for-gene) of infection by pathogens or feeding by insects

14. Ecological resistance

    The ability of an ecosystem to withstand or buffer against incursions and disturbances (48, 99, 133)

15. Resilience

    The ability of a system to recover from disturbance; alternatively, the magnitude of disturbance required to cause a permanent shift in composition and/or disturbance regime (48, 99, 133, 153)

16. Tit-for-tat

    In an iterative prisoner's dilemma, the strategy of reciprocity consisting of initial cooperation followed by copying the other player's moves

17. Sentinel trees

    The strategic use of trees in new or existing plantations and gardens for international (pre-introduction) or domestic (post-introduction) pest surveillance

18. Tolerance

    Relating to a plant, the ability to withstand infection or herbivory asymptomatically and/or with minimal impact on growth and/or fecundity

19. Insect-phytopathogen complex

    A plant disease whose manifestation requires both feeding activity of a vector or non-vector insect(s) and infection by a pathogen(s)

20. Host resistance breeding

The progressive selection and propagation of genes or genotypes in plant populations to improve host resistance to pests

Sidebar: Institutional responses to laurel wilt and myrtle rust

Poignantly, scientists in the US sounded the alarm for a decade as laurel wilt disease (LWD) caused by Raffalea lauricola and its ambrosia beetle vector rampaged through native forests in Florida. It was only when LWD hit the avocado industry that action was directed by inter-institutional committees such as the National Plant Board to try to slow the spread of the disease, and then only to protect avocado. The avocado industry in Florida has since lost over 25% of its producing land area (62, 228). LWD continues to spread and threaten an entire family of woody flowering plants in the eastern US, and avocado production and the center of Lauraceae diversity in Latin America (74, 91, 106, 147, 168). Likewise in Australia, which harbors over half of global diversity of the plant family Myrtaceae (~2,250 species), eradication campaigns for myrtle rust were prematurely abandoned due to commercial considerations. This action was taken despite a verifiable threat to ~350 native species of trees, including *Eucalyptus* spp., which constitute over 75% of forested area in the country (32). Note: we still have 23 words to give in this sidebar.

Figures

Fig. 1. A conceptual model of the biological phases (colors) of invasions of forest insects and pathogens and corresponding social actions and policies (blue arrows). Dotted line depicts pest population size and geographical extent (y axis) of invasions over time (x axis), and axis labels describe some positively correlated attributes of social costs and risks. This graphical representation is not intended to be proportional or empirical. *Management includes silvicultural, chemical, behavioral and biological control.

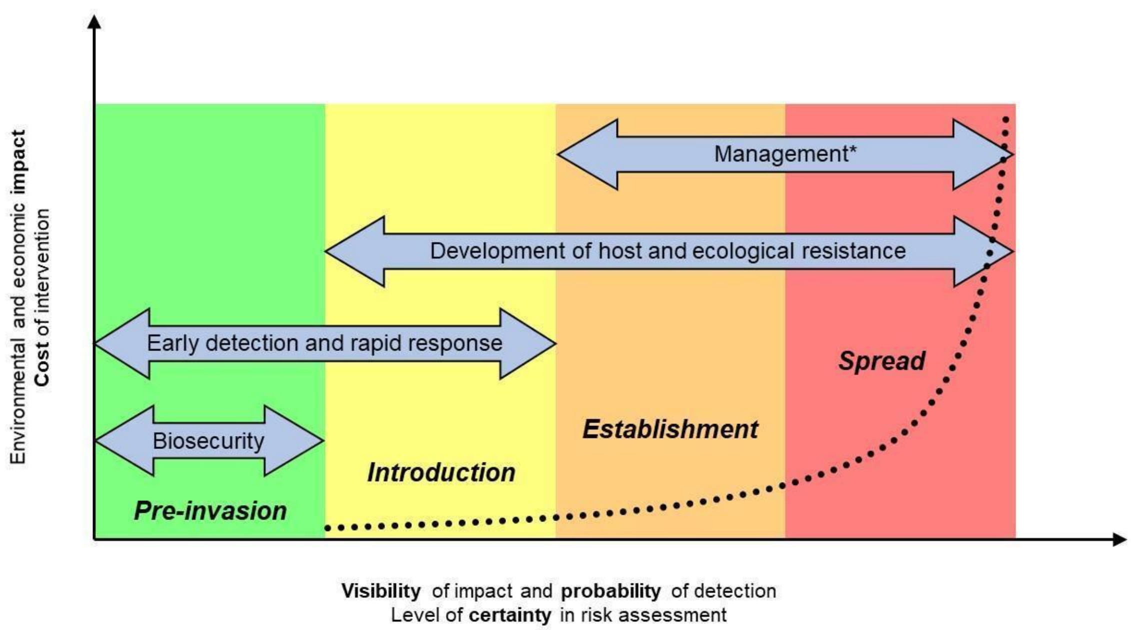

Fig. 2. Alternative stable states of global forest health and society in the face of increasing volumes of global trade and climate change. Circles represent the reinforcing effect of the interacting components on one another, which push forest health (and societal and ecological systems) towards either resilience or crisis.