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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 enables scientists to better engage policymakers and empowers the public to advocate for proactive biosecurity and forest health management. Collective action in forest health features 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 nonmarket 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.

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 well-being, 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 (16)—are at an ecological tipping point (157).

Among the drivers of such losses, biological invasions by forest pests (insects and pathogens) that kill or otherwise severely reduce the productivity of trees at landscape and regional scales have become all too common (30, 129). These biological invasions constitute a societal grand challenge that needs to be addressed simultaneously with climate warming, food and income insecurity, environmental destruction, loss of biodiversity, and emerging human and animal infectious diseases (83, 122). 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 (10, 89, 143).

Biological invasions are primarily driven by human activity and amplified by advances in technology and trade. Beginning in the twentieth 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 (54, 129, 133, 136). These encounters led to devastating, landscape-transforming epidemics affecting iconic tree species, including pine wilt disease in Eurasia (*Bursaphelenchus xylophilus*, vector *Monochamus* spp.) (104); white pine blister rust in North America (*Cronartium ribicola*) (91); Dutch elm disease (*Ophiostoma novo-ulmi*, vector *Scolytus* spp.) and chestnut blight (*Cryphonectria parasitica*) in Eurasia and North America (91); and myrtle rust (*Austropuccinia psidii*) (52) throughout Australia/Oceania and the Paleotropics. This crisis is not unique to native forests (158); for example, the European wood-wasp (*Sirex noctilio*) and its pathogenic fungal symbiont threaten the sustainability of exotic pine plantations in South America (23), Africa, and Australia (69).

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 (41, 93). In the United States 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 (41, 117). Tens or hundreds of megatonnes of carbon are being released annually (e.g., 12.5 Mt/y in the United States alone; 123) by the decimation of trees that are recognized as ecological and/or cultural keystone species such as oaks (*Quercus* spp.) (22), ashes (*Fraxinus* spp.) (24, 48, 68, 115), beeches (*Fagus* spp.) (14, 38), multiple species of cedars and cypresses (family Cupressaceae) (57, 75, 152), and laurels (family Lauraceae) (108). North America has also been a source of highly destructive insects and pathogens on other continents, such as *Ceratocystis platani*, which kills planetrees in Europe and the Middle East (86, 147), and pine wilt disease (104), the red turpentine beetle (*Dendroctonus valens*) (164), and fall webworm (*Hyphantria cunea*) in East Asia (163). Even as the fallout from host species loss reverberates through ecosystems and economies, new destructive insects and pathogens continue to accumulate (11, 93, 131). Meanwhile, concomitant losses of biodiversity and positive feedback with climate change amplify the vulnerability of forests to new biological invasions (29, 58, 71, 121, 125).

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 ʻŌhiʻa 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 (6, 24, 46, 47, 100). In Japan, the 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 (39). Rural poverty in Appalachia (USA) 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., 96).

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 United States President's State of the Union Address since 1990 and "invasive" has never been used (9); 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.

The unrecognized crisis of forest insect and pathogen invasions is epic in its proportions and demands a proportional global response. Owing 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 (53, 112, 158). 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 (158), reforestation, and afforestation efforts as well as assisted migration campaigns currently being undertaken to combat climate change (13, 117), particularly as nursery stock is a prime vector for destructive pathogens of woody plants (11, 77).

Invasive species: include established, reproducing, and dispersing population(s) that disrupt ecosystems (or agroecosystems) outside their native range

Common-pool resource: a resource such as fisheries, air quality, or forest health for which benefits, damages, and responsibility are shared among stakeholders

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

Clearly, the crisis of forest insect and pathogen invasions demands urgent action. 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 (84, 107), we developed a consensus on the major challenges preventing policy success in the realm of forest health and invasive species (see 7) that summarized the state of the science in the context of the consensus position, proposed an integrated framework for addressing forest health threats, and provided an action plan for addressing the major challenges. This approach, typically used in the context of interdisciplinary and transdisciplinary team science, relies on an iteration of ideas and convergence toward shared understanding of scientific language, knowledge, and perspectives.

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 and safeguard human health and well-being. 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 heritage and must be recognized as such if they are to be properly protected. Insofar as they regulate carbon cycling and contribute to global biodiversity, forests are known to constitute a common-pool resource on a global scale (see 110). Although protecting forests from invasive pests is mutually beneficial to all (37), 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 the adoption of collective action.

The failure of the world's current institutions and policies to effectively safeguard forest health stems from a poor alignment between the public-good nature of the problem and the 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 (94). 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 resources, including forest tree species, against economic gain (106, 109).

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 (11, 129). These agreements include the 1995 Sanitary and Phytosanitary Standards (SPS) Agreement (162), which delegates power to the International Plant Protection Convention, first entered into in 1952 (32, 129) to develop standards for "clean" shipments. Even assuming general compliance with the standards that have been set under these agreements, the number of non-native insects and pathogens that become established and the damage they cause continue to accumulate worldwide (12, 133). The current wording, lack of urgency in adopting stronger rules, and insufficient enforcement illustrate how economic interests are weighed heavily, whereas the high nonmarket 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 (11, 129). The major concern of the WTO agreements is to "ensure that unnecessary health and safety regulations are not used as an excuse for protecting domestic producers from foreign competition" (162), ostensibly balancing trade with health; clearly, the main interest of the organization is trade and commerce. Continued prioritization of access to overseas markets over the sustainability of domestic natural resources ensures that the failures of the international phytosanitary status quo—namely, its insufficient accommodation of precautionary phytosanitary actions, sanctions, and enforcement—go unremarked and uncorrected. In fact, the current international phytosanitary status quo is akin to the perceived "optimal strategy" of a prisoner's dilemma (110), in that cooperative action taken by an exporter is detrimental without matching investment among partners. 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 nonmarket losses, i.e., most ecosystem services (87, 129). However, this strategy is perceived as less desirable owing to the short-term monetary sacrifices it entails, leading to the tragedy of the commons (110) that is the forest health crisis and unsustainable environmental destruction.

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

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 (110). We argue that an integrated approach to combat the forest health crisis should embrace a collective action framework (4, 55, 111) that incorporates the following principles of stakeholder engagement and empowerment (4, 25, 37, 161):

- 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 because of 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 (85, 110). As with these other public goods, non-native insects and pathogens do not respect political boundaries. However, the investment costs of solutions to the forest health crisis are borne differently across various governments, industries, and landowners, whereas the benefits (i.e., the public goods) are realized on a global scale. Together, these attributes make the forest health crisis a social dilemma (55). Success at tackling such a public-good social dilemma—and ultimately realizing a reduction in invasive insect and pathogen introductions and impacts and more effective control of active outbreaks—requires a baseline, threshold amount of investment and sustained collective action from all stakeholder groups across scales (4, 55).

There are numerous tactical solutions that can help address the forest health crisis in small but important ways in the short term. To solve the public-good social dilemma in the long term, sustained collective action that incorporates the aforementioned principles of stakeholder engagement and empowerment is necessary and requires coordination among a multitude of stakeholders whose worldviews, perspectives, and interests are often largely at odds (i.e., it is a "wicked problem;" see 161). It also requires a dynamic political process for effective and equitable negotiations and compromises. 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 (31, 131, 133).

Biosecurity: protective measures taken to prevent the introduction of organisms that could threaten biological resources or people

Ecological resistance: the ability of an ecosystem to withstand or buffer against incursions of pests, their establishment, and associated disturbances

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

AN AGENDA FOR REFORM AND THE CONSTRAINTS IT FACES

Efforts at each stage of the policy development process—(*a*) agenda setting, (*b*) policy formulation, and (*c*) implementation—are critical for shaping the trajectory of policy (128) to combat the forest health crisis. As discussed below, this crisis presents unique challenges at each stage of the process that include institutional constraints, the difficulty of generating political will to protect forest health through a traditionally economic paradigm, and 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 (66), framing the debate about forest pest invasions as part of the global forest health crisis will have significant influence on policy outcomes. Effective, persuasive (i.e., emotive), and evidence-driven messaging that underscores the high nonmarket value of the global forest biome and its connection to environmental sustainability and agricultural productivity is also critical to motivate receptive participants in the policy arena.

Paradigm-shifting societal and environmental disturbance events provide an opportunity for the public and their leaders to reassess their value system and implement reforms (37), perhaps shifting the window of viable policy solutions toward collective action approaches. 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 forest health risks. Such phytosanitary risks add to other ecological (24) and social (43) concerns raised by so-called nature-based climate solutions. For these reasons, both the 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 principles:

- 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, culture, 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 increase forest ecological resistance and resilience (see 62, 154).
- 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 that narrow the range of feasible solutions. Currently, much public perception of invasive species could be characterized as invasion fatigue (e.g., 160). 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 (130, 137). Stakeholder engagement can address such apathy by contributing to mutual trust, agreeing on a common goal, establishing perceived self-efficacy, and empowering the public to make a difference (21, 137), as recently demonstrated by the popularity of the "Don't Move Firewood" campaign in the United States in response to invasions by wood-boring insects (129).

Economic risk assessment: the process of assessing risk based on probability of establishment, expected impact, and economic value of resources threatened by a biological threat

Current forest protection policy is most critically constrained by a lack of recognition for the broader cultural, aesthetic, and intrinsic values of forestlands, including the 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.

Implementation

In the implementation stage, policies that build trust and increase coordination among the public, scientists, forestry and wood product professionals, and policymakers are critical to cultivating 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 (45), many are not well-known in their native range or are even new to science (11, 76), and they typically behave in new and unpredictable ways in their expanded range (109, 129). 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 (20). 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 (20, 109, 129).

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 (44). The downstream effects of this skewed focus can be irreversible, as exemplified by the stories of governmental response to LWD in the United States (see the sidebar titled Institutional Response to Laurel Wilt) and myrtle rust in Australia (see the sidebar titled Institutional Response to Myrtle Rust). 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 United States, Australia, and around the globe.

INSTITUTIONAL RESPONSE TO LAUREL WILT

Scientists in the United States sounded the alarm for a decade as laurel wilt disease (LWD) caused by *Raffaelea 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 more than 25% of its producing land area (36, 155). LWD continues to spread and threaten an entire family of woody flowering plants in the eastern United States and avocado production and the center of Lauraceae diversity in Latin America (108).

INSTITUTIONAL RESPONSE TO MYRTLE RUST

In Australia, which harbors more than half of the global diversity of the plant family Myrtaceae (∼2,250 species in Australia), eradication campaigns for myrtle rust were prematurely abandoned because of commercial considerations. This action was taken in spite of stakeholder concerns and despite a verifiable threat to ∼350 native species of trees, including *Eucalyptus* spp., which constitute more than 75% of forested area in the country (17). Myrtle rust continues to devastate native Myrtaceae in Australia and New Zealand and is poised to cause numerous extinctions of beloved, culturally and ecologically important native tree species.

A COLLECTIVE ACTION FRAMEWORK TO PROTECT FOREST HEALTH

Many terms, frameworks, and concepts to describe strategies to minimize the impact of biological invasions—which focus predominantly on plants and not on insects or pathogens (113, 114, 159)—have been reviewed elsewhere and accompanied by substantial disagreement about how to frame the invasion process (79, 94, 127). Invasion context may also include social, economic, cultural, and ecological considerations (**Figure 1**).

An integrated framework to address forest pests should incorporate (*a*) more effective biosecurity to prevent new introductions; (*b*) increased monitoring for early detection and improved preparedness for rapid response to outbreaks; (*c*) management, including silvicultural treatment

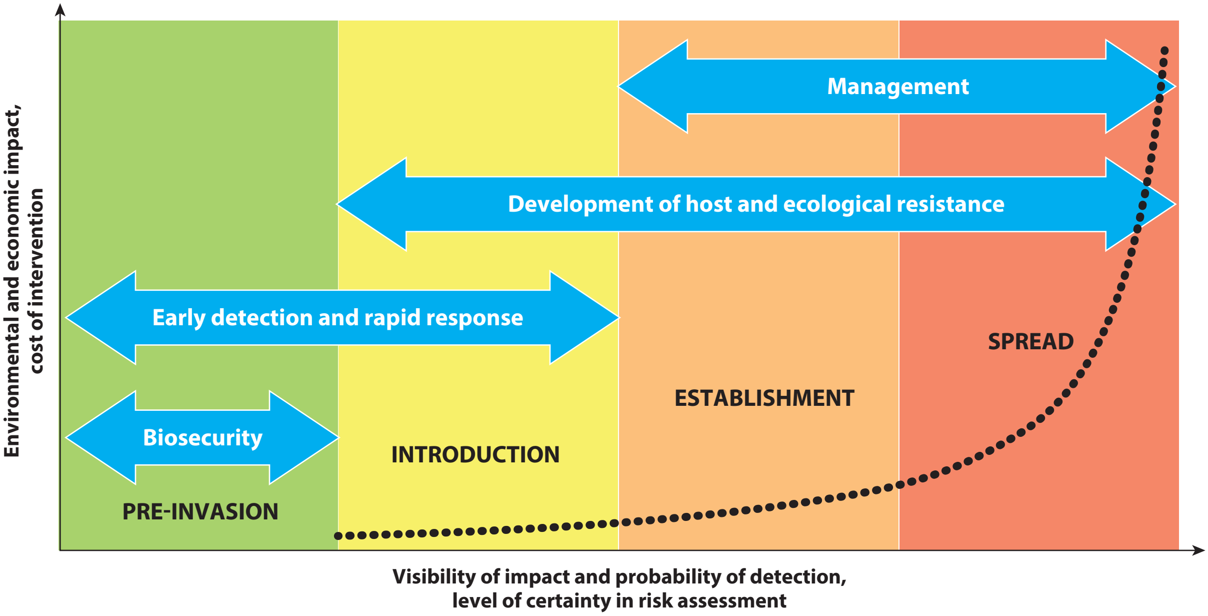

Figure 1

A conceptual model of the biological phases of invasions of forest insects and pathogens: pre-invasion (*green*), introduction (*yellow*), establishment (*orange*), and spread (*red*), and corresponding technical interventions (*blue arrows*). Management includes silvicultural, chemical, behavioral, and biological control. The dotted line depicts increases in environmental, economic, and intervention costs (*y axis*) of invasions as their visibility and certainty (*x axis*) increase with pest population size and geographical extent over time. This graphical representation is not intended to be proportional or empirical.

(e.g., sanitation and salvage), chemical suppression, and behavioral control and biological control; (*d*) development of host resistance (general); and (*e*) management of forests to promote ecological resistance and resilience to invasion. These approaches can be mapped onto successive introductory, establishment, and spread phases of invasion (7) (**Figure 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 (**Figure 1**). In the remainder of this section, we discuss how incorporating collective action principles into 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.

Sanitation: a silvicultural operation aimed at removing pathogens and insect pests present in a given area by removing trees harboring them

Salvage: a silvicultural operation in which trees that are killed or damaged by pathogens and/or insect pests are felled to recoup otherwise lost economic value

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

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

Biological control: the introduction, augmentation, or conservation of predators, pathogens, and competitors to regulate pest populations in invaded ecosystems

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, corporations, and nations will "think globally, act locally" 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 (64) or green labeling (129). However, global trade contributes substantially to human well-being 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.

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 and 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 (SMART) enforcement of penalties for noncompliant shipments. In addition to stepping up customs enforcement, the USDA-APHIS (US Department of Agriculture–Animal and Plant Health Inspection Service) "Not Authorized Pending Pest Risk Assessment" (NAPPRA) rule or a similar designation by national plant protection organizations (NPPOs) outside of the United States 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 (50, 51, 54, 92). 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 (e.g., 144) 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 (20). 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 trees, both native species and close relatives, planted abroad support pre-invasion detection for high-risk species and commodities (33, 98, 105, 112, 144). 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.

A second component of Tree-SMART trade is the use of pest-free packaging material (pallets, crates, dunnage, etc.) in international shipments (92). This will require significant trust-building, goal-setting, and resource sharing among stakeholders because of potential impacts on allies in the forestry sector and wood products industry. Phasing out wood packaging could threaten local economies and industries. With stakeholder support, processed wood (e.g., oriented strand board), recycled plastic, and even fungi could be used as pest-free alternatives (74).

Host resistance (general): relating to a plant, relative minimization (quantitative) or nearly absolute prevention (gene-for-gene) of infection by pathogens or feeding by insects

Early detection and rapid response: effective monitoring and surveillance that leads to timely detection and ultimately triggers effective containment and eradication of invasive pest incursions

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

Monitoring and surveillance: the use of visual inspections, traps, remote sensing, molecular detection, and other technologies to detect pests

Early Detection

Globalization is a fundamental aspect of modern society, but universal responsibility for the social dilemma it entails in protecting natural systems is not readily apparent or perceived as tractable to individuals. Biosecurity monitoring and surveillance policies in the United States and European Union, 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 United States, and only a fraction of species present in pathways worldwide have been intercepted, while some commonly invading taxonomic groups are hardly detected at all (34, 59, 88, 148). 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 are only somewhat effective for wood-boring beetles and of little utility against most sap-feeding insects (124). Air and soil traps combined with molecular tools are also increasingly employed for fungal and oomycete pathogens (e.g., 18). For years, remote sensing in the form of traditional aerial photography–based surveillance 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 due 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, 8, 15, 129, 145).

Clearly, there is a need for even more coordinated effort, common goal setting, and pooling of resources to ramp up surveillance efforts to keep pace with the continually rising volume of international trade (31). Collective action has the potential to greatly improve capacity to detect pests in time to achieve a successful response. For example, in the United States, 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 the Neotropics, Paleotropics, Asia, and Oceania (19, 56, 148), where invasions are expected to increase in the future (134). 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 (31).

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) could be supported in dedicating higher levels of surveillance to wood packaging if it were 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 (**https://www.publicgardens.org/programs/sentinel-plant-network/about-spn**). Such inter-institutional arrangements might be expanded to give a broader set of stakeholders a voice in 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. 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 United States, is highly restricted 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 responses to pests after detection (11, 37). These mismatches stem from a lack of common goals, inadequate support for weakest-link actors, and failure to accommodate stakeholder-driven local adaptation (4). 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 (11, 17); on the other hand, when the immediate risk affects less economically important hosts, institutions are slow to act (see the sidebars Institutional Response to Laurel Wilt and Institutional Response to Myrtle Rust).

Successful response can often be credited to collective action (4). 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 bridges to more centralized national and/or international pest management authorities.

In the United States, 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 (150). The TWPP and specialty crops programs could support a 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 (63, 95, 105).

In the longer term, centralized guidance modeled on the Centers for Disease Control and Prevention (CDC) or Federal Emergency Management Agency in the United States, the European Centre for Disease Prevention and Control in the European Union, and the World Health Organization would enable more rapid detection and coordinated response (8, 37, 110). Such a model is outlined briefly in the section titled Institutional and Societal 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 (see the sidebars Institutional Response to Laurel Wilt and Institutional Response to Myrtle Rust).

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 (161). 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.

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

Through cooperative interagency efforts, including the TWPP in the United States, spread and damage have been greatly reduced in some cases by setting goals to prioritize problematic invasive insects (118) and 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* (90, 146). Silvicultural pest management strategies have contributed to successful local eradication and containment of Asian long-horned beetle *Anoplophora glabripennis* in the United States (90, 146) and control of white pine blister rust in Korea (82) and China (165).

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. Although 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 organophosphates and neonicotinoids, the latter of which includes the same chemicals often used to drench or inject individual trees for emerald ash borer in urban areas in the United States (135, 149). Questions have been raised regarding the environmental cost, particularly to pollinator populations, of aerial applications in pine forests in Asia. On the other hand, convergence of local interests around the control of the emerald ash borer in urban areas has allowed for some success in mitigating loss of urban tree cover while boosting perceptions of self-efficacy (see 21) among citizens.

The intensity and high level of stakeholder involvement required from private landowners can contribute to fatigue, apathy, and a perceived lack of self-efficacy regarding the larger issue of invasive species. Domestically, interagency working groups such as the National Invasive Species Council and nongovernmental organizations such as The Nature Conservancy 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 (142) and PlayCleanGo (**https://playcleango.org/**), which reduces transmission of soilborne pathogens.

Biological control has yielded substantial success against multiple invasive forest insects, especially defoliators (97, 151). Natural enemies possess the valuable properties of being self-dispersing and reproducing, complementarity to other management tactics, and functioning in a density-dependent fashion (61, 78). Biological control agents 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 (67, 78).

Despite these positive attributes, biological control has not been adequate to protect trees from pathogens (120) or when host trees show little resistance or tolerance to the pest to allow for natural enemy buildup (73, 81). Such instances include some of the most damaging, ecosystem-altering invasive organisms that are currently arriving in disproportionately high frequencies (3). Likewise, biological control has had relatively little success against invasive bark and wood-boring insects (but see 69) and even less against insect–phytopathogen complexes (120). Additionally, the utility of natural enemies can be constrained by higher trophic interactions and climatic mismatches in their introduced zone (132, 154).

Insect–phytopathogen complexes: plant diseases whose manifestation requires both feeding activity of a vector or nonvector insect(s) and infection by a pathogen(s)

Host resistance breeding: the progressive selection and propagation of genes or genotypes in plant populations to improve host resistance to pests

Breeding for Host Resistance

Host resistance breeding can provide an environmentally safe, bottom-up approach to combat established threats (136). In tree species most affected by novel pests, there is often a low frequency of genetically resistant individuals, and these are 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 (139, 140). Classical and biotechnology-assisted breeding includes the use of markers, transgenic and gene-editing technologies (26), and emerging tools for rapid phenotyping (e.g., 153). Importantly, in a collaborative approach, host breeding efforts could leverage sentinel plantings in plantations, urban forests, and genetic resources such as seed orchards and progeny trials (33, 98) and use citizen scientists to monitor these trees for biological stressors (70, 156).

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 (28, 40, 138, 140). Disease-resistant populations of *Castanea dentata*, *Ulmus americana*, and, more recently, *Fraxinus* spp. are also in various stages of development, approval, deployment, and improvement (80). Indigenous tribes are taking a lead role in the deployment of resistant populations, including establishment of seed orchards (R. Sniezko, unpublished results).

The continued and growing utility of host resistance to manage the forest health crisis into the future depends on the broad application of collective action principles, including agreements to prioritize target species based on economic, cultural, and ecological importance (102, 117, 118). Success also depends on long-term, pooled investment in infrastructure to develop and deploy resistance into the landscape (8, 42, 106, 136, 140) if it is to successfully incorporate both host and pathogen diversity (156).

Much-needed public support for breeding is mounting (72, 106), particularly for transgenic resistance. This includes the major breakthrough with American chestnut (*C. dentata*) (119), which, as a famously functionally extinct species, offers opportunities to garner future support for host breeding (156) and beyond. Another success story, improved resistance of whitebark pine (*Pinus albicaulis*) to *Cronartium ribicola*, has led to an integrated, collaborative, cross-institutional species restoration plan that has helped garner public support (103). 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 (141).

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. 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. The resistance and resilience of forests and society can be enhanced by incorporating collective action principles into forest management systems (37) and improving the ability of various stakeholders to take proactive steps to protect forest health and mount a robust response to forest insect and pathogen invasions.

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 can lead to permanent community shifts, including costly functional extinctions and losses of productivity (60). Resistance and resilience (62) against disturbances caused by invasions are therefore central to a holistic approach to protecting forests from invasive species (see 99).

Forest stand and landscape composition and structure, which can be modified by management practices, have implications for pest outbreaks (99) and, therefore, invasion biology. Diversity is integral to bolstering and sustaining forest resistance and resilience to biological disturbances (99), including invasive species. Genetic and structural diversity of plant communities can be promoted at stand and landscape scales by management based on natural disturbance regimes and at the landscape scale by using locally adapted material and applying traditional ecological knowledge (5, 27, 71, 99). 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 (99). For example, susceptible species are sometimes protected by neighboring nonhosts (associational resistance), the accumulation of invasive pests is diminished by higher forest tree diversity, and pest damage increases with lower nonhost diversity (58, 71). A lack of top-down regulators like natural enemies in degraded or low-diversity forests is also thought to be an important factor in the facilitation of biological invasions (65, 136). 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 the tropics, highlighting the need for investment from resource-rich trading partners (19) and free exchange of information. Moreover, success in adaptation to 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 pooling resources to support research 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 (*a*) coalition building, (*b*) robust research and development funding, and (*c*) reorganization of NPPO models are needed to sustain these measures and push forests and society into a positively reinforcing alternative stable state (**Figure 2**).

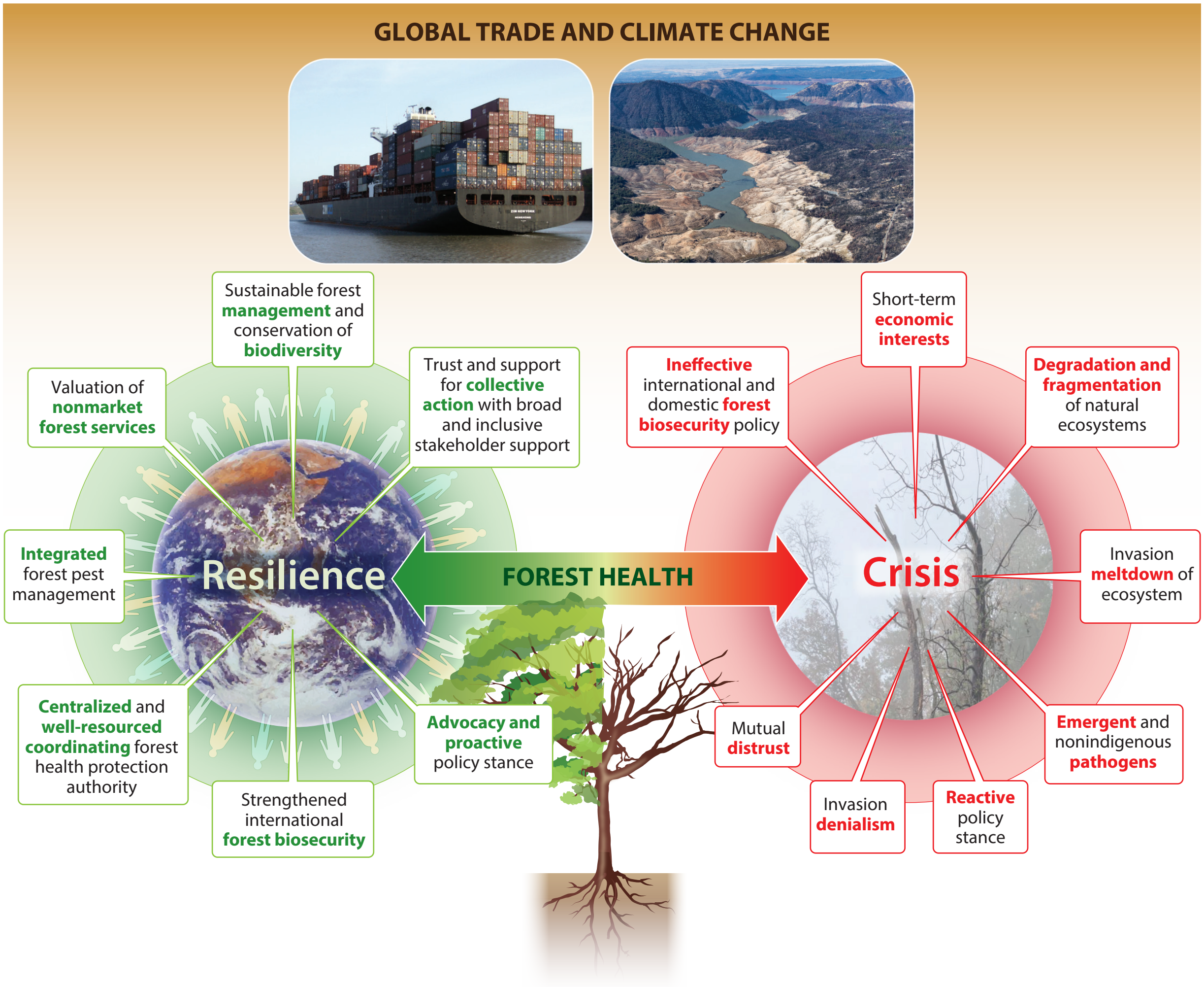

Figure 2

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 pushes forest health (and societal and ecological systems) toward either resilience or crisis. Lake Oroville photo courtesy of California Department of Water Resources. Shipping container photo reproduced from Rolf H./Wikimedia Commons (**https://commons.wikimedia.org/wiki/File:ZIM_New_York_(ship,_2002)_002.jpg**) (CC BY 2.0).

Above all, achieving strong international biosecurity, integrated domestic pest management, sustained and comprehensive research funding, and a proactive policy stance inevitably require building an inclusive global coalition. The effectiveness and longevity of such a strategy hinge on leadership, collective action principles (4, 37, 55, 110), and the ability of scientists and advocates to develop and communicate the costs and benefits of proactive versus reactive policy (e.g., 87) through a compelling, emotionally engaging narrative. Such efforts must emphasize the significance of forests to the public and policymakers.

An effort to better connect local-level stakeholders is central to addressing the crisis. In the United States, making a case for the support of indigenous advocates may be an effective strategy to place the intrinsic value (e.g., 103) 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 (5, 126). Sporting and outdoor enthusiasts should also be natural advocates because of their stake in fishery, wildlife, and foraging habitat. Recruiting, training, and collaborating with citizen scientists could also constitute a powerful human resource for advocacy, monitoring, and implementation of restoration efforts (116). 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.

Collective action could leverage the existing efforts and infrastructure of cities and municipal governments, nongovernmental soil and water conservation districts, and stakeholder groups. Support of certification groups (49) could also lead to incentivization of proactive monitoring and pest management on private lands. Bringing such a diverse set of stakeholders together behind a common set of priorities and goals is essential for collective action.

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 nongovernment stakeholders and agencies in the United States (8). We advocate that such models be bolstered and adopted not only in the United States but also by other governmental and nongovernmental bodies. CFPCPs would also play an analogous role to the CDC to build trust with the public through focused science communication (130).

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 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, the Intergovernmental Platform on Biodiversity and Ecosystem Services, the Natural Resources Defense Council, and the International Union of Conservation of Nature and Natural Resources.

A STRATEGY FOR ADVOCACY TO SHIFT THE PARADIGM

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. Although 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 is essential to emphasize that healthy forests protected from, and resilient to, invasive insects and pathogens are 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 (21), 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 the 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 as well as the large costs to municipalities and residents of losing urban forest cover (e.g., 35, 101). Lessons from previous social dilemmas reveal the power of such a public groundswell.

Forest health specialists are 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 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 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 multitiered international movement to make "think global, act local" a societal norm is the principal long-term challenge posed by the global forest health crisis (110, 111).

SUMMARY POINTS

1. The challenge posed by biotic invasions is inherently international in scope and universal in consequence.
2. The forest health crisis is intimately connected with many of the most prominent and existential grand challenges to ecological and economic sustainability in the Anthropocene.
3. 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.
4. 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.
5. 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

1. To achieve a common vision and build and sustain the collective will to do so, leaders must empower, engage, and listen to a broader stakeholder base.

2. Owing 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, lower- and middle-income countries, the conservation of biodiversity, and collective action to address climate change.
3. Policy must also take into account the intrinsic, cultural, and nonmarket value of forest ecosystems in risk assessment and proactive decision-making processes.
4. Ultimately, stakeholder empowerment will lead to a wider societal embrace and collective will for stewardship of biodiversity and a more resilient society.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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All authors contributed to the conceptualization and writing of the article. 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 article writing and editorial process also included multiple rounds of feedback as well as written and intellectual contributions from all the authors.

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LITERATURE CITED

1. Adams DC, Olexa MT, Reynolds T. 2018. Invasive alien species policy: incremental approaches and the promise of comprehensive reform. *Drake J. Agric. Law* 23:292–342
2. Aiko S, Duncan RP, Hulme PE. 2010. Lag-phases in alien plant invasions: separating the facts from the artefacts. *Oikos* 119:370–78
3. 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. *BioScience* 60:886–97
4. **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* 5:343–51**
5. Berkes F, Colding J, Folke C. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecol. Appl.* 10(5):1251–62
6. Billie JE. 2014. Beetles killing our "tu lee" must be stopped. *Seminole Tribune*, Febr. 26. **https://seminoletribune.org/beetles-killing-our-tu-lee-must-be-stopped/**
7. **Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, et al. 2011. A proposed unified framework for biological invasions. *Trends Ecol. Evol.* 26:333–39**
8. **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**
9. Borevitz B. 2021. State of the Union. *State of the Union*. **http://stateoftheunion.onetwothree.net/**
10. Boyd IL, Freer-Smith PH, Gilligan CA, Godfray HCJ. 2013. The consequence of tree pests and diseases for ecosystem services. *Science* 342(6160):1235773
11. Brasier CM. 2008. The biosecurity threat to the UK and global environment from international trade in plants. *Plant Pathol.* 57(5):792–808
12. Brockerhoff EG, Liebhold AM. 2017. Ecology of forest insect invasions. *Biol. Invasions* 19(11):3141–59
13. 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
14. 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
15. Cappaert D, McCullough DG, Poland TM, Siegert NW. 2005. Emerald ash borer in North America: a research and regulatory challenge. *Am. Entomol.* 51(3):152–65
16. Carlowicz M. 2012. Seeing forests for the trees and carbon: mapping the world's forests in three dimensions. *NASA Earth Observatory*. **https://earthobservatory.nasa.gov/features/ForestCarbon/page1.php**
17. Carnegie AJ, Pegg GS. 2018. Lessons from the incursion of myrtle rust in Australia. *Annu. Rev. Phytopathol.* 56:457–78
18. Chandelier A, Hulin J, San Marin G, Debode F, Massart S. 2021. Comparison of qPCR and metabarcoding methods as tools for the detection of airborne inoculum of forest fungal pathogens. *Phytopathology* 111(3):570–81
19. 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.* 52:291–314
20. 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
21. 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):1088–99
22. 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*. *Earth's Future* 8(7):e2020EF001500
23. 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.* 92:131–42

4. A review and meta-analysis that identifies the most critical collective action principles in plant invasion dilemmas.

7. Critical meta-analysis of terminology and process models applied to invasive, alien, introduced, and naturalized species.

8. Introduces the concept of Centers for Forest Pest Control and Prevention.

24. 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):435–46
25. Cox M, Arnold G, Tomás SV. 2010. A review of design principles for community-based natural resource management. *Ecol. Soc.* 15(4):38
26. Dort EN, Tanguay P, Hamelin RC. 2020. CRISPR/Cas9 gene editing: an unexplored frontier for forest pathology. *Front. Plant Sci.* 11:1126
27. 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.* 36:2285–99
28. 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
29. 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.* 39:231–48
30. 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.* 7:12485
31. Epanchin-Niell R, McAusland C, Liebhold A, Mwebaze P, Springborn MR. 2021. Biological invasions and international trade: managing a moving target. *Rev. Environ. Econ. Policy* 15(1):180–90
32. 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. Policy* 51:228–37
33. 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
34. Eschen R, Roques A, Santini A. 2015. Taxonomic dissimilarity in patterns of interception and establishment of alien arthropods, nematodes and pathogens affecting woody plants in Europe. *Divers. Distrib.* 21:36–45
35. Escobedo FJ, Adams DC, Timilsina N. 2015. Urban forest structure effects on property value. *Ecosyst. Serv.* 12:209–17
36. Evans EA, Crane J, Hodges A, Osborne JL. 2010. Potential economic impact of laurel wilt disease on the Florida avocado industry. *HortTechnology* 20:234–38
37. Evans KJ, Scott JB, Barry KM. 2020. Pathogen incursions: integrating technical expertise in a socio-political context. *Plant Dis.* 104:3097–109

37. Considers sociopolitical dimensions of invasive plant pathogens and treats plant health as a common-pool resource.

38. Ewing CJ, Hausman CE, Pogacnik J, Slot J, Bonello P. 2019. Beech leaf disease: an emerging forest epidemic. *Forest Pathol.* 49:e12488
39. 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. Space* 43:1079–97
40. Farjon A. 2013. *Chamaecyparis lawsoniana*. *IUCN Red List Threat. Species* 2013:e.T34004A2840024
41. Fei S, Morin RS, Oswalt CM, Liebhold AM. 2019. Biomass losses resulting from insect and disease invasions in US forests. *PNAS* 116:17371–76
42. 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, ed. RA Sniezko, AD Yanchuk, JT Kliejunas, KM Palmieri, JM Alexander, SJ Frankel. Albany, CA: USDA
43. 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):947–50
44. Food Agric. Organ. (FAO). 2009. *Global review of forest pests and diseases*. For. Pap. 156, FAO, Rome. **https://www.fao.org/3/i0640e/i0640e00.htm**
45. Franić I, Prosepro S, Adamson K, Allan E, Attorre F, et al. 2022. Worldwide diversity of endophytic fungi and insects associated with dormant tree twigs. *Sci. Data* 9:62
46. Gallagher PB. 2014. Redbay trees are dying. *Seminole Tribune*, Febr. 25. **https://seminoletribune.org/redbay-trees-are-dying/**

47. Gallagher PB. 2015. Much research, few answers as laurel wilt disease spreads. *Seminole Tribune*, July 1. **https://seminoletribune.org/much-research-few-answers-as-laurel-wilt-disease-spreads/**
48. Gandhi KJK, Herms DA. 2010. North American arthropods at risk due to widespread *Fraxinus mortality* caused by the alien emerald ash borer. *Biol. Invasions* 12:1839–46
49. Garzon ARG, Bettinger P, Siry J, Abrams J, Cieszewski C, et al. 2020. A comparative analysis of five forest certification programs. *Forests* 11(8):863
50. 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.* 5:869–78
51. Gilbert GS, Webb CO. 2007. Phylogenetic signal in plant pathogen-host range. *PNAS* 104:4979–83
52. 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 Pathol.* 36:1–16
53. 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
54. Gougherty AV, Jonathan DT. 2021. Towards a phylogenetic ecology of plant pests and pathogens. *Philos. Trans. R. Soc. B* 376:20200359
55. 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.* 33:275–87
56. 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
57. Green S, Elliot M, Armstrong A, Hendry SJ. 2015. *Phytophthora austrocedrae* emerges as a serious threat to juniper (*Juniperus communis*) in Britain. *Plant Pathol.* 64:456–66
58. Guo Q, Fei S, Potter KM, Liebhold AM, Wen J. 2019. Tree diversity regulates forest pest invasion. *PNAS* 116:7382–86
59. 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
60. Hadziabdic D, Bonello P, Hamelin RC, Juzwik J, Moltzan B, et al. 2021. The future of forest pathology in North America. *Front. For. Glob. Change* 4:737445
61. Hajek AE, Eilenberg J. 2018. *Natural Enemies*: *An Introduction to Biological Control*. Cambridge, UK: Cambridge Univ. Press. 2nd ed.
62. Halpern CB. 1988. Early successional pathways and the resistance and resilience of forest communities. *Ecology* 69(6):1703–15
63. Hamelin RC, Roe AD. 2020. Genomic biosurveillance of forest invasive alien enemies: a story written in code. *Evol. Appl.* 13(1):95–115
64. Hantula J, Müller MM, Uusivuori J. 2014. International plant trade associated risks: laissez-faire or novel solutions. *Environ. Sci. Policy* 37:158–60
65. Heger T, Jeschke JM. 2014. The enemy release hypothesis as a hierarchy of hypotheses. *Oikos* 123:741–50
66. Howlett M, Ramesh M, Perl A. 2009. *Studying Public Policy*: *Principles and Processes*. Oxford, UK: Oxford Univ. Press
67. Hufbauer RA, Roderick GK. 2005. Microevolution in biological control: mechanisms, patterns, and processes. *Biol. Control* 35:227–39
68. Hultberg T, Sandström J, Felton A, Öhman K, Rönnberg J, et al. 2020. Ash dieback risks an extinction cascade. *Biol. Conserv.* 244:108516
69. Hurley BP, Slippers B, Wingfield MJ. 2007. A comparison of control results for the alien invasive woodwasp, *Sirex noctilio*, in the Southern Hemisphere. *Agric. For. Entomol.* 9:159–71
70. Ingwell LL, Preisser EL. 2011. Using citizen science programs to identify host resistance in pest-invaded forests. *Conserv. Biol.* 25(1):182–88
71. Jactel H, Moreira X, Castagneyrol B. 2021. Tree diversity and forest resistance to insect pests: patterns, mechanisms, and prospects. *Annu. Rev. Entomol.* 66:277–96
72. 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. Policy Econ.* 80:167–77

73. 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. *Agric. For. Entomol.* 18:327–39
74. Jones M, Mautner A, Luenco S, Bismarck A, John S. 2020. Engineered mycelium composite construction materials from fungal biorefineries: a critical review. *Mater. Des.* 187:108397
75. 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* 83:3167–81
76. 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
77. Jung T, Orlikowski L, Henricot B, Abad-Campos P, Aday AG, et al. 2015. Widespread *Phytophthora infestans* in European nurseries put forest, semi-natural and horticultural ecosystems at high risk of *Phytophthora* diseases. *For. Pathol.* 46(2):134–63
78. Kenis M, Hurley BP, Hajek AE, Cock MJ. 2017. Classical biological control of insect pests of trees: facts and figures. *Biol. Invasions* 19(11):3401–17
79. 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
80. Koch JL, Carey DW, Mason ME, Poland TM, Knight KS. 2015. Intraspecific variation in *Fraxinus pennsylvanica* responses to emerald ash borer (*Agrilus planipennis*). *New For*. 46:995–1011
81. Krause SL, Raffa KF. 1996. Defoliation tolerance affects the spatial and temporal distributions of larch sawfly and natural enemy populations. *Ecolog. Entomol.* 21:101–11
82. La Y-J. 2009. Korean successes in controlling blister rust of Korean pine. In *Proceedings of the Breeding and Genetic Resources of Five-Needle Pines Conference*, ed. D Noshad, E Noh, J King, R Sniezko, pp. 1–9. Vienna: IUFRO
83. 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. *Aquat. Conserv.* 30:194–208
84. Laursen B. 2018. What is collaborative, interdisciplinary reasoning? The heart of interdisciplinary team science. *Inf. Sci. Int. J. Emerg. Transdiscipl.* 21:75–106
85. Lee DJ, Adams DC, Kim CS. 2009. Managing invasive plants on public conservation forestlands: application of a bio-economic model. *For. Policy Econ*. 11(4):237–43
86. Lehtijärvi A, Oskay F, Dogmus Lehtijärvi HT, Aday Kaya AG, Pecori F, et al. 2018. *Ceratocystis platani* is killing plane trees in Istanbul (Turkey). *For. Pathol.* 48:e12375
87. 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.* 12:273–79
88. 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.* 10:135–43
89. Liebhold AM, Brockerhoff EG, Kalisz S, Nuñez MA, Wardle DA, Wingfield MJ. 2017. Biological invasions in forest ecosystems. *Biol. Invasions* 19:3437–58
90. Liebhold AM, Kean JM. 2019. Eradication and containment of non-native forest insects: successes and failures. *J. Pest Sci.* 92:83–91
91. Loo JA. 2009. Ecological impacts of non-indigenous invasive fungi as forest pathogens. *Biol. Invasions* 11(1):81–96
92. Lovett G, Weiss M, Lambert KF. 2019. Preventing the importation of invasive forest pests through Tree-SMART trade. *Entomol. Soc. Am.* **https://eco.confex.com/eco/2020/meetingapp.cgi/Paper/86805**
93. Lovett GM, Canham CD, Arthur MA, Weathers KC, Fitzhugh RD. 2006. Forest ecosystem responses to exotic pests and pathogens in eastern North America. *BioScience* 56:395–405
94. 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.* 26:1437–55
95. Luchi N, Ioos R, Santini A. 2020. Fast and reliable molecular methods to detect fungal pathogens in woody plants. *Appl. Microbiol. Biotechnol.* 104:2453–68
96. Lutts RH. 2004. Like manna from God: the American chestnut trade in southwestern Virginia. *Environ. Hist.* 9:497–525
97. 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

98. 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* 48:1–24
99. Marini L, Ayres MP, Jactel H. 2022. Impact of stand and landscape management on forest pest damage. *Annu. Rev. Entomol.* 67:181–99
100. 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 Stud. Environ.* 4(1):11041185
101. 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):137–50
102. 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
103. 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*, ed. RE Keane, DF Tomback, MP Murray, CM Smith, pp. 226–34. Fort Collins, CO: USDA
104. Mota M, Vieira P, eds. 2008. *Pine Wilt Disease*: *A Worldwide Threat to Forest Ecosystems*. Dordrecht, Neth.: Springer
105. Munck IA, Bonello P. 2018. Modern approaches for early detection of forest pathogens are sorely needed in the United States. *For. Pathol.* 48:e12445
106. Natl. Acad. Sci. Eng. Med. 2019. *Forest Health and Biotechnology*: *Possibilities and Considerations*. Washington, DC: Natl. Acad. Press
107. Natl. Res. Counc. 2005. *Facilitating Interdisciplinary Research*. Washington, DC: Natl. Acad. Press
108. Olatinwo RO, Fraedrich SW, Mayfield AE. 2021. Laurel wilt: current and potential impacts and possibilities for prevention and management. *Forests* 12(2):181
109. Ormsby M, Brenton-Rule E. 2017. A review of global instruments to combat invasive alien species in forestry. *Biol. Invasions* 19:3355–64
110. Ostrom E. 1990. *Governing the Commons*: *The Evolution of Institutions for Collective Action*. Cambridge, UK: Cambridge Univ. Press
111. Ostrom E. 2010. A multi-scale approach to coping with climate change and other collective action problems. *Solutions* 1:27–36
112. Paap T, Burgess TI, Wingfield MJ. 2017. Urban trees: bridgeheads for forest pest invasions and sentinels for early detection. *Biol. Invasions* 19:3515–26
113. Paap T, Wingfield MJ, Burgess TI, Hulbert JM, Santini A. 2020. Harmonising the fields of invasion science and forest pathology. *NeoBiota* 62:301
114. Paap T, Wingfield MJ, Burgess TI, Wilson JRU, Richardson DM, Santini A. 2022. Invasion frameworks: a forest pathogen perspective. *Curr. For. Rep.* 8:74–89
115. Pautasso M, Aas G, Queloz V, Holdenrieder O. 2013. European ash (*Fraxinus excelsior*) dieback: a conservation biology challenge. *Biol. Conserv.* 158:37–49
116. Pawson SM, Sullivan JJ, Grant A. 2020. Expanding general surveillance of invasive species by integrating citizens as both observers and identifiers. *J. Pest Sci.* 93:1155–66
117. Pike CC, Koch J, Nelson CD. 2021. Breeding for resistance to tree pests: successes, challenges, and a guide to the future. *J. For.* 119:96–105
118. 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
119. Powell WA, Newhouse AE, Coffey V. 2019. Developing blight-tolerant American chestnut trees. *CSH Perspect. Biol.* 11:a034587
120. 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
121. Pureswaran DS, Roques A, Battisti A. 2018. Forest insects and climate change. *Curr. For. Rep.* 4:35–50
122. Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, et al. 2020. Scientists' warning on invasive alien species. *Biol. Rev.* 95(6):1511–34

109. Review of current instruments aimed at curbing forest invasive species and their history.

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

123. 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. Change* 4:143
124. 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. *Am. Entomol.* 65(1):29–42
125. 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* 89:245–52
126. 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. *Restor. Ecol.* 27(1):3–8
127. 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. Invasions* 22:2633–45
128. Rosenbaum WA. 2020. *Environmental Politics and Policy*. Washington, DC: CQ Press. 11th ed.
129. **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):457–65**

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

130. Russell JC, Blackburn TM. 2017. The rise of invasive species denialism. *Trends Ecol. Evol.* 32:3–6
131. 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.* 197:238–50
132. Schultz AN, Lucardi RD, Marsico TD. 2019. Successful invasions and failed biocontrol: the role of antagonistic species interactions. *BioScience* 69(9):711–14
133. Seebens H, Blackburn T, Dyer E, Genovesi P, Hulme PA, et al. 2017. No saturation in the accumulation of alien species worldwide. *Nat. Commun.* 8:14435
134. **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. Change Biol.* 21:4128–40**

134. Identifies growing threat to biodiversity in emerging economies.

135. Shin SC. 2008. Pine wilt disease in Korea. In *Pine Wilt Disease*, ed. BG Zhao, F Kzauyoshi, JR Sutherland, Y Takeuchi, pp. 26–32. Dordrecht, Neth.: Springer
136. 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
137. 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
138. 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
139. 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
140. **Sniezko RA, Koch J. 2017. Breeding trees resistant to insects and diseases: putting theory into application. *Biol. Invasions* 19:3377–400**

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

141. Sniezko RA, Liu JJ. 2021. Prospects for developing durable resistance in populations of forest trees. *New For.* **https://doi.org/10.1007/s11056-021-09898-3**
142. Solano A, Rodriguez SL, Coyle DR. 2020. *The Nature Conservancy's Don't Move Firewood campaign: an analysis of the 2005–2016 survey data*. Rep., For. Environ. Conserv., Clemson, SC. **http://www.dontmovefirewood.org/wp-content/uploads/2020/07/Solano-Rodriguez-and-Coyle-DMF-Report-for-2005-2016-Survey-Data_2.pdf**
143. **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**

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

144. 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):1942–45
145. Theoharides KA, Dukes JS. 2007. Plant invasion across space and time: factors affecting nonindigenous species success during four stages of invasion. *New Phytol.* 176:256–73
146. Tobin PC, Kean JM, Suckling DM, McCullough DG, Herms DA, Stringer LD. 2014. Determinants of successful arthropod eradication programs. *Biol. Invasions* 16:401–14

147. Tsopelas P, Santini A, Wingfield M, DeBeer W. 2017. Canker stain: a lethal disease destroying iconic plane trees. *Plant Dis.* 101:645–58
148. 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
149. 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*, ed. MM Mota, PR Vieira, pp. 389–96. Dordrecht, Neth.: Springer
150. USDA. 2023. Budget. *U.S. Department of Agriculture*. **https://www.usda.gov/our-agency/about-usda/budget**
151. 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(Suppl. 1):S2–33
152. 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
153. 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
154. 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
155. Wasielewski J. 2020. *Laurel wilt*: *a disease impacting avocados*. Rep., Univ. Fla. Inst. Food Agric. Sci. Ext., Gainesville, FL. **https://sfyl.ifas.ufl.edu/miami-dade/agriculture/laurel-wilt---a-disease-impacting-avocados/**
156. 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
157. Wilson EO. 2016. *Half-Earth*: *Our Planet's Fight for Life*. New York: Norton
158. Wingfield MJ, Brockerhoff EG, Wingfield BD, Slippers B. 2015. Planted forest health: the need for a global strategy. *Science* 349:832–36
159. Wingfield MJ, Slippers B, Wingfield BD, Barnes I. 2017. The unified framework for biological invasions: a forest fungal pathogen perspective. *Biol. Invasions* 19:3201–14
160. 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. Invasions* 6(4):319–28
161. 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
162. World Trade Organ. (WTO). 2010. *Sanitary and phytosanitary measures*. Rep., WTO, Geneva. **https://www.wto.org/english/res_e/booksp_e/agrmntseries4_sps_e.pdf**
163. 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.* 3:105–15
164. 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.* 14:1735–60
165. Zhang XY, Lu Q, Sniezko R, Song RQ, Man G. 2010. Blister rusts in China: hosts, pathogens, and management. *For. Pathol.* 40:369–81

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

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Errata

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