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Fundamental Economic Irreversibilities Influence Policies for Enhancing International Forest Phytosanitary Security

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Abstract National and international efforts to manage forest biosecurity create tension between opposing sources of ecological and economic irreversibility. Phytosanitary policies designed to protect national borders from biological invasions incur sunk costs deriving from economic and political irreversibilities that incentivizes wait-and-see decision-making. However, the potential for irreversible ecological and economic damages resulting from failed phytosanitary policies argues for precautionary measures, creating sunk benefits while increasing the risk of over-investment in phytosanitary security. Here, we describe the inherent tension between these sources of irreversibility in economic terms, relate these forces to type I and type II errors, and use this framework to review national and international efforts to protect forests from biological invasions. Available historical evidence suggests that wait-and-see phytosanitary decision-making has dominated the adoption of precautionary measures in most regions and that willingness to under-regulate may sometimes be orders of magnitude greater than willingness to over-regulate. Reducing scientific uncertainty about threats to biosecurity may help mitigate the tendency to under-regulate, and phytosanitary security measures with relatively modest sunk costs could help protect forests as scientific learning advances. A fuller accounting of the costs associated with type II errors,

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particularly regarding the suite of non-market ecosystem services at risk, would help decision-makers better understand the trade-offs between the sunk costs of policies and long-term economic losses to stakeholders.

Keywords Cost-benefit analysis · Externality · Non-market value · Option value · Precautionary principle · Risk · Quasi-option value · Stock effect · Uncertainty

Introduction

The essential problems in the economics of forest phytosanitary security involve unraveling a web of complex, long-term and uncertain relationships linking international trade, forest ecology, and economic values so that efficient allocations of effort to plant biosecurity can be identified and implemented. Risk (states-of-the world that are amenable to probabilistic descriptions) and uncertainty (states-of-the-world that defy probabilistic descriptions) affect phytosanitary decisions and often necessitate taking action beforehand to prevent subsequent undesirable outcomes [1]. Many invasive species have long lag times between the time of establishment and the point at which economic impacts become fully manifest [2], suggesting that not only will the establishment of new species become problematic, but also the legacy of past biosecurity failures will continue to present surprising and undesirable outcomes well into the future [3]. Advances in recent research have shown that invasive species prevention is the policy with the greatest long-term net economic benefit [4••]. This perspective, combined with new knowledge highlighting the economic vulnerability of forest ecosystem services to biological invasions [1, 5–8, 9••] has contributed to calls for increasing the degree of precaution embodied in forest phytosanitary regulations [10••, 11].

Non-native organisms pose a rapidly increasing biosecurity threat to forest ecosystem services and values around the world. Data going back to the early 1800s show that the number of non-native forest insect species in the USA has increased at roughly a linear rate since 1860, resulting in the detection of about 2.5 species year^{-1} and roughly 0.5 year^{-1} have caused substantial economic damage [12].[1] Although most introductions of nonindigenous forest insects into the USA have resulted from trade with Europe, rapid growth in the volume of USA imports arriving from Asia during the past three decades has resulted in an increasing trend in the detection of non-native phloem and wood-boring insects arriving from that region [12]. A similar long-term trend is evident in Europe where historical records demonstrate an exponential increase (roughly 0.43% year^{-1}) in the number of non-native forest pathogens over two centuries, with most pathogens arriving from North America [13], and a roughly linear increase in the number of new insect species established on woody plants [14].

Forest biosecurity depends upon recognizing and acting upon the risks associated with organisms traveling along major pathways that threaten domestic forest health. The major historical pathway (nearly 70%) for forest insect and pathogen invasions of the USA appears to be live plant imports [15]. Untreated wood packing material has been another important pathway for wood-boring insects into the USA [16] and New Zealand [17]. Similarly, non-native forest pathogens have primarily been introduced into Europe via live plants (57%) or wood (10%) [13] and the shipment of raw logs among European countries have recently been implicated in the introduction of non-native forest insects and diseases from Russia and Baltic countries to Belgium [18].

In economic terms, biological invasions of plant communities are externalities (unintended consequences) of the international movement of goods and reflect a market failure. Those who gain directly from international trade in plant-related products (off-shore producers, merchant groups, consumers of those products) typically differ from those who pay the consequences (domestic agriculture and forestry operations, consumers of environmental quality, taxpayers), thereby causing an unintended transfer of wealth. Economists have argued that market failures associated with invasive species might be addressed using the "polluter pays" principle to internalize the externality, that is, by imposing taxes on those who cause the externality in amounts that are commensurate with the economic damages avoided [19–21].

However, the polluter-pays approach to forest biosecurity suffers several weaknesses. First, trade policy is susceptible to the influence of political interest groups seeking to gain advantage from trade barriers disguised as instruments to prevent biological invasions [22]. Second, determining optimal tariffs (Pigouvian taxes) that would internalize the costs of biological pollution imposes stringent information requirements in determining economic benefits (damages avoided) of control [23]. Third, although biological invasions may have long-term or irreversible effects on forest ecosystems, non-native pests and pathogens often remain latent for long periods and damages may only become manifest many years after introduction and establishment [3]. Thus, the economic benefits of prevention are greatly diminished when they are discounted to initial prevention dates [2]. Fourth, there are no mechanisms currently in place under international trade rules promulgated by the World Trade Organization (WTO) to internalize costs from biological invasion externalities [21]. Finally, illegal importation of propagative and other material has caused new pest establishments in recent decades and the tighter the restrictions on legitimate imports, the more likely it is for smuggling to occur [R Griffin, *personal communication*].

[1] The rate of increase has declined somewhat since the early 1900s.

In the absence of mechanisms for implementing the polluter-pays principle, the primary approach for protecting agricultural and forest ecosystems from non-native pests and pathogens has been the promulgation of federal legislation, regulations, policies, and international agreements—which, for the sake of convenience, we subsume under the general descriptors “policy” and “policy actions.” A fundamental tension exists between economic and ecological irreversibilities inherent in policy actions that are taken to reduce the risk of damaging environmental outcomes in the future. Economists have recognized that information develops over time and that waiting for information has economic value both in terms of making investments (option value) and in protecting the environment (quasi-option value). In the following sections, we illustrate how these economic concepts are related to type I and type II errors as used in statistics and review evidence that biosecurity agencies tend to minimize sunk costs at the risk of increasing ecological irreversibilities. This framework is then used to consider national and international efforts to protect forest resources from biological invasions. Available estimates of economic damages caused by non-native forest insects and diseases are discussed and alternatives are presented for mitigating future damages by enhancing phytosanitary security. Finally, we present the conclusions that may be drawn from this review.

Opposing Economic and Ecological Irreversibility in Phytosanitary Decision-Making

Promulgation of phytosanitary laws, regulations, and policies entail economic and political commitments that are not easily reversible and therefore represent sunk costs (e.g., restricted trade flows, costs of border inspections, and required phytosanitary treatments). Uncertainty regarding the ultimate destructiveness of non-native organisms, combined with economic and political sunk costs deriving from policy responses, suggest that a wait-and-see strategy can be rational [24].[2] If decision-makers are optimistic that the growth in scientific knowledge is rapid enough such that current and future protective actions will be good substitutes, it may be optimal to wait for information before establishing new policies [25]. However, waiting for information increases the risk that irreversible damages accrue during the waiting period [26••]. Further, biological pollution resulting from the successful establishment of non-native organisms induces cumulative (stock) effects in which ecological and associated economic damages are magnified [27, 28] and facilitate the possibility of invasional meltdown [29]. Policies designed to address long-term environmental concerns, such as threats to human well-being deriving from the loss of biological diversity, are burdened by substantial uncertainty and must confront trade-offs between the sunk costs and sunk benefits of alternative options [30, 31]. Decisions regarding the optimal timing and stringency of phytosanitary policies therefore critically depend upon beliefs regarding the nature of opposing economic and ecological irreversibilities and the anticipated magnitude of sunk costs and sunk benefits [26••].

To understand how sunk costs can induce decision-makers to wait-and-see before taking action on phytosanitary protection, consider the following argument (based on the introductory model in [32], p. 27–30] describing the logic of financial options). Suppose that a decision-maker is considering establishing a policy that would protect tree health from a novel pathogen and the policy requires a completely irreversible investment which costs \$600 (I_0, the sunk cost, at $t = 0$). The expected economic benefit (B) of the policy at present is $E[B_0] = \$1000$ (Fig. 1). Scientific uncertainty regarding the virulence of the pathogen is resolved in a future period ($t = 1$), and it is assumed that the probability (p) of high virulence (hv) and the probability (1-p) of low virulence (lv) are equal ($p = 1–p = 0.5$). If, at $t = 1$, the pathogen is learned to be highly virulent, the expected benefit of investing in the policy at that point increases to $E[B_1^{hv}] = 1.5E[B_0] = \$1500$ and if the threat is learned to be non-virulent, the expected benefit of the policy decreases to $E[B_1^{lv}] = 0.5E[B_0] = \$500$. From the vantage point of the present ($t = 0$), immediately implementing the policy seems to make sense, as the expected net benefit ($E[NB_1]$) is positive:

$$E[NB_1] = E[B_0]\text{-}I_0 = \$400 \quad (1)$$

However, this calculation ignores the opportunity cost of investing now, rather than investing after scientific uncertainty is resolved. From the vantage point of the future ($t = 1$), the possible economic and political downside of investing in a policy that ultimately protects against a minor threat is a negative expected net benefit ($E[NB_2]$):

$$E[NB_2] = E\left[B_1^{lv}\right]\text{-}I_0 = \text{-}\$100 \quad (2)$$

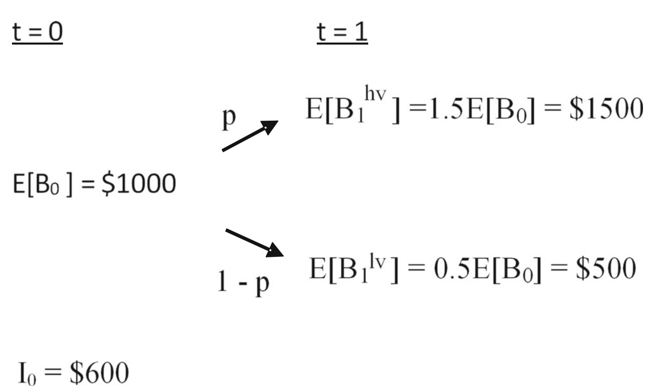

Fig. 1 Simple example of the option value of a phytosanitary policy

[2] However, as noted in [24], if a biological invader is highly damaging and spreads rapidly, decisions should not be delayed.

It is the possibility of (over) investment in a policy that ultimately yields negative political and economic consequences that provides an incentive to delay the policy decision until the actual virulence is known ($t = 1$).

Alternatively, if it is ultimately learned that this novel pathogen is highly virulent, then the expected net benefit ($E[NB_3]$) of the policy is positive:

$$E[NB_3] = E\left[B_1^{hv}\right] - I_0 = \$900 \quad (3)$$

The difference $E[NB_3] - E[NB_1]$ is known as the option value and represents the expected economic value of delaying a policy decision until scientific uncertainty is resolved. In this example, the option value of delaying policy implementation equals $500.

However, what is not considered in this simple example is that expectations may be wrong (due to pervasive uncertainty), surprises happen, and damaging events may be initiated while waiting for better information. Biological invasions in forests limit opportunities for consuming a full suite of future forest ecosystem services and environmental economists have pointed out that when actions (including no action) restrict future opportunities, and environmental irreversibility is involved (such as the loss of biological diversity), one should bias decisions in favor of the environment to protect future environmental options [33]. This economic principle is known as quasi-option value and is conceptually equivalent to the financial theory of option value [34]. That is, the option to postpone investment in a new phytosanitary policy has value because a decision-maker can learn about the severity of a threat, and the necessity of protection, by waiting. And the implementation of precautionary phytosanitary policy has value because a decision-maker can thereby wait for information about the benefits of protecting ecosystems before they are altered, incurring potentially irreversible ecological and economic damages. It is the inherent tension between these two expressions of value that becomes manifest in public debate regarding phytosanitary policy [26••].

Type I and Type II Errors

Scientists describe two types of mistakes that can be made when testing hypotheses or, more generally, establishing environmental policy [35, 36]. If it is concluded that an effect exists when in fact it does not, this is called a type I error, or false positive. Alternatively, concluding that an effect does not exist when in fact it does exist is called a type II error, or false negative. These concepts can be related to concerns expressed by option and quasi-option values. That is, policies that are biased towards the avoidance of irreversibilities arising from sunk costs are consistent with the minimization of type I errors (over-regulation) (Fig. 2). Policies that are biased towards the avoidance of environmental irreversibilities exhibit precaution by minimizing type II errors (under-regulation).

It has been argued that the design of environmental policy should balance the probability of making each type of error (E_I and E_{II}) against their relative costs (C_I and C_{II}) [37•, 38]:

$$\frac{E_{II}}{E_I} = \frac{C_{II}}{C_I} \quad (4)$$

This approach would require agencies managing invasive species to explicitly consider the acceptable levels of risk associated with type II errors they are willing to tolerate. Evidence suggesting that biosecurity agencies tend to minimize the risk of type I errors (over-regulation) at the expense of increasing the risk of type II errors (under-regulation) has been provided for aquatic organisms [37•].[3] This result is consistent with economic theory that, as scientific uncertainty regarding future outcomes increases, concern over the sunk costs of environmental protection will increasingly dominate policy decisions [31].

The argument developed in [37•] concerning the acceptability of incurring type II errors relative to type I errors can be extended to border protection targeted at intercepting non-native forest insects by making the following assumptions. Let the costs of making type II errors (under-regulation) be estimated using reported annual residential property losses in the USA from forest insects, $1.5 billion [9••] (a lower-bound estimate of total damages), and let the costs of making type I errors (over-regulation) be approximated by the proportion of the USA border protection budget attributable to forest insects and diseases: estimated to be $4.3 million (an upper-bound estimate).[4] While these estimates could be refined, they suggest that willingness to incur type II errors in forest phytosanitary border protection may be orders of magnitude larger than willingness to accept type I errors.

The "precautionary principle" has emerged in response to scientific uncertainty and remains one of the most contentious issues in environmental law and policy [42] while being invoked to improve phytosanitary security [43, 44]. Principle 15 of the 1992 Rio Declaration states "Where there are threats of serious or irreversible damage, lack of full scientific certainty

[3] In a study of biosecurity actions taken by a public agency to control non-native aquatic species, it was concluded that biosecurity budgets implied a willingness to accept type II errors 1007 times more than type I errors [37•]. In a related study, review of 31 non-significant empirical studies of non-native aquatic species led the authors to conclude that low statistical power led to type II error rates 5.6–19 times greater than type I error rates [39].

[4] Estimated by multiplying the Fiscal Year 2006 Presidents Budget for invasive species border protection ($137 million; [40]) times the rate of forest insect border interceptions relative to all insect interceptions (3.17%; [41]). This is likely an over-estimate of the costs of over-regulation as it assumes that all border protection costs targeted at forest insects are unnecessary. Clearly, this is not the case.

Fig. 2 Errors in plant biosecurity decision-making

	Reality	
Decision	H_0: Action not needed	H_A: Action needed
Act	Type I error (reject H_0) Over-regulate	Correct decision
Do nothing/ Inadequate action	Correct decision	Type II error (reject H_A) Under-regulate

shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." The precautionary principle, which has roots in Swedish and German law, has been a binding principle of EU environmental law since the 1992 Treaty on European Union and advocates prudence by reducing type II errors [35, 36].

Economists have considered the problem of decision-making when deep uncertainties are encountered regarding the likelihood of various outcomes and have suggested that the focus of attention be shifted from expected outcomes towards the catastrophic tail of outcome distributions [45, 46]. Policy decisions then rely on criteria that minimize consequences anticipated for the worst-case scenario (*maximin*) or that minimize the regret associated with worst-case mistakes (*minimax regret*). The *maximin* criterion is precautionary in protecting against type II errors, but can lead to costly type I errors, whereas *minimax regret* seeks to balance the costs associated with these two types of errors. A weighted form of *minimax regret*, in which weights are based upon the consequences of type II errors, has been proposed in which policy assessment relies upon estimates of the costs and benefits associated with each type of error [47].

National and International Approaches to Phytosanitary Border Security

Economic and political sunk costs are incurred with the establishment of any new phytosanitary policy [24, 26••]. When a policy is completely irreversible, greater uncertainty regarding the future costs or benefits deriving from that policy leads to a higher threshold for policy adoption [26••, 31]. However, when policy options are more easily reversible, earlier implementation of policies is favored as some sunk costs can be recouped [24]. National phytosanitary policies and international commitments are, in general, strongly irreversible and have tended to favor a wait-and-see approach for implementation.

Early plant health policy focused on specific pests known to cause damage and posing threats via international trade. The need for phytosanitary legislation was recognized during the late nineteenth century as non-native pests began ravaging agricultural, viticultural, and forest crops and as early as 1875, German laws were passed to protect domestic agriculture from the highly destructive Colorado potato beetle [48]. A similar response to this pest was instituted in the UK through The Destructive Insects Act of 1877 [49]. Concern with damage to domestic apple orchards caused by a non-native moth introduced from Europe led New Zealand to pass the Codling Moth Act in 1884 and a few years later (1896), a more general act (the Garden Pests Act) was passed which sought to prevent the introduction of any "plant, fungus, parasite, insect or any other thing which… is likely to introduce any disease into the colony" [50]. The first agreement for international cooperation in phytosanitary security, the International Convention on Measures to be taken against *Phylloxera vastatrix*, was adopted in 1878 by seven countries and resulted from establishment of an insect pest of grape vines introduced from the USA which caused devastating losses to vineyards throughout Europe, Australia, and South Africa [51, 52].

Within the USA, it was not until passage of the Plant Quarantine Act of 1912 that agricultural and natural ecosystems were intentionally protected from non-native insects and pathogens. It has been argued that "Until 1912 the United States was the only great nation which was not protected by law from importation of insect pests and … this country was said to have been the dumping ground for refuse nursery stock … The imported insect pests and plant diseases introduced prior to 1912 were at that time causing a loss in farm products estimated at about $1,000,000,000 annually" [53]. A section of this Act included Quarantine 1, which prohibited the importation of five-needle pines and was prompted by an ongoing outbreak of white pine blister rust and widespread alarm triggered by the rapid expansion of chestnut blight [54].

Expanding global concern with phytosanitary security led to the 1929 International Convention for the Protection of Plants and included participants from 49 countries [52]. However, only 12 countries eventually ratified the Convention and the outbreak of World War II delayed further international progress on plant protection. Following the Second World War, hopes for global economic recovery and political stability were thought to be best satisfied by increasing international trade, which posed new threats to phytosanitary security [51]. International efforts resulted in the creation of the General Agreement on Tariffs and Trade (GATT) in 1947, which was superseded by the World Trade Organization (WTO) in 1995. The goal of the WTO is to stimulate world trade by removing trade barriers and providing a binding mechanism for settling disputes among member countries [55].

Ongoing concerns about the impacts of rapid growth in international trade on plant health were addressed in 1951 with the creation of the International Plant Protection Convention (IPPC), formed under the auspices of the newly created (1945) Food and Agriculture Organization. The goal of the IPPC is to prevent the introduction and spread of plant pests and pathogens by providing a framework for international cooperation between National Plant Protection Organizations (NPPOs) who are contracting parties to the IPPC (currently 183 parties). The IPPC coordinates efforts with the WTO regarding provisions for plant protection in international trade.

Since 1995, risks to plant health posed by international trade are addressed by the WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) [56]. Under the SPS Agreement, any limits on trade must be based on standards or science-based measures (known as International Standards on Phytosanitary Measures, or ISPMs) established by the IPPC. In 1996, ISPM2, Guidelines for Pest Risk Analysis, was adopted and requires formal pest risk analyses be completed to inform plant risk protection decisions regarding new regulations. The IPPC requires all consequences of biological invasions be described in economic terms and ISPM11, instituted in 2004, clarified the role of economic analyses in pest risk assessment. This measure states that both the market and non-market economic consequences of a pest should be determined using quantitative or qualitative measures. The potential for unacceptable economic consequences can help provide evidence that an organism is a pest and the estimated magnitude of the consequences can then help determine the stringency of phytosanitary measures [57].

The IPPC established an international standard for wood packing material, ISPM15, in 2002 and this standard has been adopted by over 70 of the 177 signatory countries to the IPPC [58]. Within the USA, interception data before and after the implementation of ISPM15 indicated that this measure decreased infestations by about 52% [59]. The increased cost of heat treatments or fumigation required by this standard has had minor impacts on trade flows and was estimated to cause economic losses to consumers in the USA of $437 million or roughly 0.004% of household welfare [58]. The benefits of reducing damage to residential forests from imposition of this standard are estimated to increase rapidly in coming decades, attaining an expected net present value of $11.9 billion by the year 2050 [60]. Although ISPM15 was fully adopted in the USA in 2006, several years after the establishment of Asian longhorned beetle and emerald ash borer [58], this standard provides an efficient means of protecting forest option values (the benefits of protecting options for future generations greatly outweigh the costs).

Although contracting parties to the IPPC must comply with their obligations, countries have their own regulatory history and design, represented by their NPPO, and therefore latitude is allowed in how countries ensure their phytosanitary safety. Variation in phytosanitary regulatory design across countries reflects differences in approaches to risk management [61]. Some countries (including within the EU and the USA) use black lists of plant pests and pathogens that are deemed to cause injurious harm and therefore subject to quarantine legislation. If a black list pest is identified on an import shipment, a risk assessment is conducted to justify regulating the associated pathway. While this strategy may be sufficient for known pests and pathogens, it is insufficient for new, unknown, or underestimated organisms that may threaten plant biosecurity [22, 43] and is biased towards a wait-and-see approach.

Other countries, such as New Zealand and Australia, employ a precautionary approach to phytosanitary security by utilizing white lists identifying species that have been evaluated ex ante and found to be acceptable for importation. This strategy biases importation decisions towards protection of agricultural and natural ecosystems by minimizing type II errors and the Biosecurity Act adopted in New Zealand in 1993, which represents the most comprehensive and stringent national legislation for preventing invasive species, has resulted in a dramatic drop in the introduction of non-native organisms [62•]. An intermediary approach to phytosanitary risk management is being tested in the USA (known as Not Authorized Pending Pest Risk Assessment). This initiative attempts to balance the risks of making type I and type II errors using gray lists that subject new commodities to plant risk analysis prior to importation and is being used for decisions regarding propagative material [61].

Phytosanitary security in the European Union is dictated by the EU Plant Health Directive (adopted in 2000) which stipulates that controls are excluded at borders between member states and should be established at the Community level. The Directive, which requires the use of plant passports providing evidence of compliance with the Directive, failed to prevent the establishment and spread of ash dieback disease, *Chalara fraxinea*, first reported in the UK in 2012 and linked to the import of ash seedlings from continental Europe. It has been argued that the Plant Health Strategy adopted by the UK in

2014, in response to concerns about ash dieback and other tree insects and diseases, appears to favor commercial interests over the wider public risks to forests and that "…the considerable media and political activity should be noted as far too late to have any effect" [63], p.43].

Mitigating Trends in Forest Insect and Pathogen Establishment Rates

Phytosanitary efforts to protect plant health are often implemented too late due to inadequate scientific understanding [64], and plots of historical data suggest that, in some regions and for some forest insects and pathogens, threats to forest health are continuing to increase at a rapid rate (Fig. 3). Particularly, worrisome trends include the rapid increase of forest pathogens and insects on woody plants in Europe and the upward trend in the number of new wood borers in the USA.

Differences in historical trading patterns and biogeography suggest that not all trading partners present equivalent risks in biological invasions [65]. Species accumulation theory argues that the rate of introduction of non-native species from specific geographic regions slows as the cumulative amount of trade from those regions increase [66]. Thus, forecasts of future trade volume from a set of trading partners, in combination with data on cumulative species introductions, can be used to identify trade regions that are likely to become new sources of forest invasive species.

Using data on non-native forest insect establishment dates and international trade values from the USA (1790–2006), it is evident the cumulative number of all newly established non-native forest insects has historically increased at a decreasing rate (i.e. a concave curve) when plotted over cumulative trade value [10••], (Fig. 4). However, a more nuanced pattern is revealed when data are partitioned by species feeding guild. While a concave curve appears to reasonably represent the historical accumulation of exotic wood-boring pests from the early 1800s until the mid-1980s, the rate of species accumulation rapidly increased at a roughly linear rate roughly from 1985 to 2004. This trend likely reflects an increased use of containerized shipping during this period as well as escalating trade with Asia, especially China, beginning in the 1980s [10••]. Given that Asia harbors a diverse but relatively little-known assembly of phloem- and wood-boring insects, it is likely that this community was historically "undersampled" because of limited trade. The diminishing slope of the linear trend after about 2004 may reflect US requirements implemented in 1999 for treating wood packing material in shipments from China.

It is increasingly popular to view biosecurity as a continuum necessitating a holistic, systems-based approach to determining optimal phytosanitary measures. A systems approach includes two or more independent measures that may be applied pre- and/or post-harvest beginning in the area of origin and moving to the packing house, shipment, and distribution of a commodity [55]. Availability of data on the efficacy and practicality of multiple phytosanitary measures currently limits full application of a systems approach, and ISPM14 (2002) states that "A systems approach may include measures that are added or strengthened to compensate for uncertainty due to data gaps, variability, or lack of experience in the application of procedures." An example of a systems approach used for the export of untreated logs required consignments be: (1) free of

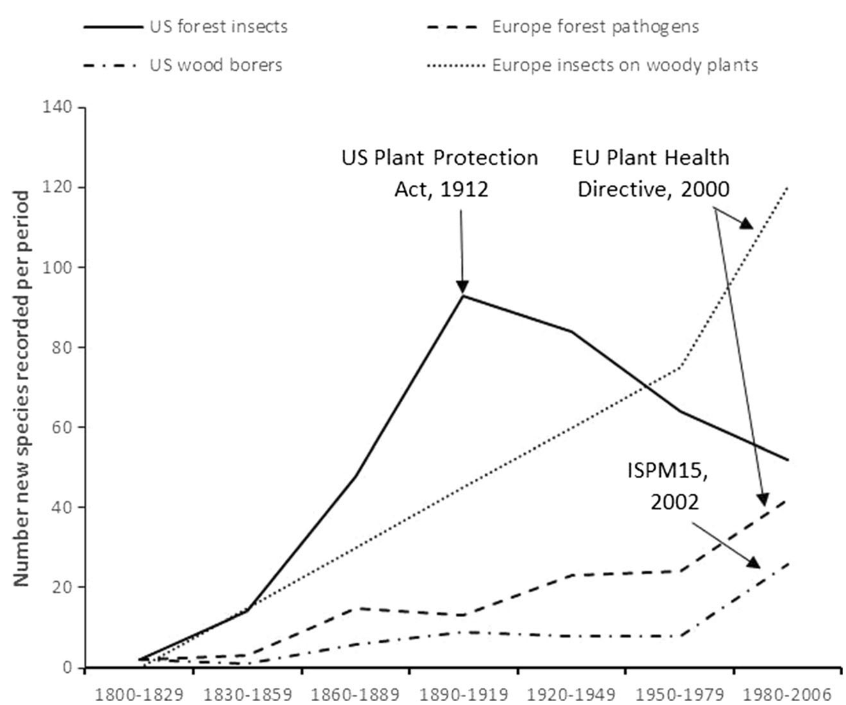

Fig. 3 Historical establishment rates of insects and pathogens affecting US and European forests. (US data from [12]; European forest pathogen data from [13, Table S1]; European insects on woody plants approximated from [14])

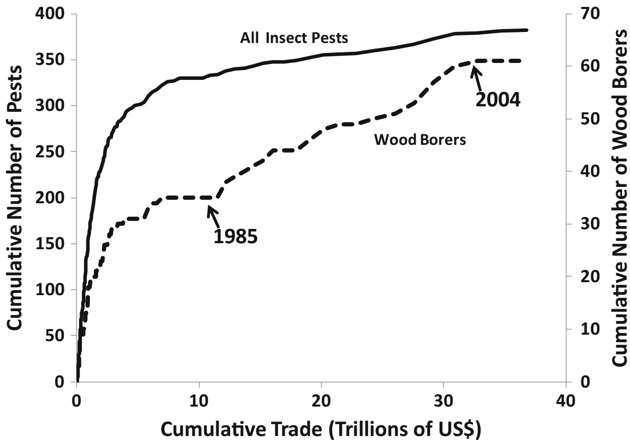

Fig. 4 Cumulative detections of all non-native forest insects (*solid line*) and wood-boring insects (*dashed line*) in the US relative to cumulative value of US imports (*dotted line*). Forest insect data from [12]. Trade data from US Census Bureau, Statistical Abstract of the US, various years; adjusted to 2010 dollars using the wholesale price index

visible pests prior to shipment, (2) transported during a low risk period, (3) unloaded and stored in a zone that is free of suitable plant hosts, and (4) fumigated within days of entry and then immediately processed [67]. An emerging role for economic analysis is understanding how a systems approach may be more effective and efficient than single phytosanitary measures.

Substituting wait-and-see policies with systems approaches for phytosanitary security will require creative solutions in order to minimize sunk costs while protecting against type II errors. Effective interventions along the biosecurity continuum requires understanding how invasive species move through trade networks so that high-risk countries can be identified [68] and it has been suggested that pre-border control of invasive species can be improved by targeting control at highly-connected nodes [69, 70]. Innovative proposals include development of early warning systems, such as installation of improved quarantine and control measures, at identified invasion hubs and establishment of sentinel tree programs with high-risk trading partners [4••, 14]. Other flexible policy options could include greater cooperation between the research community and the nursery industry to identify and deploy more effective plant management systems and the development of risk-based border inspection procedures [15]. For example, it has been demonstrated that import screening programs could be improved by decomposing pest risk assessments of nonindigenous species imports (such as plants for planting) into statistical and economic components that acknowledge the asymmetric cost of committing type I and type II errors [71].

Economic Impacts of Biological Invasions in Forests

Economic studies of the damages caused by biological invasions in forests provide lower-bound estimates of the magnitude of values at risk while remaining limited to a few regions of the world and a few types of damages to forest ecosystems.[5] Some forest economic studies have used simulation methods to address "what if" type questions, while other studies have combined observations on tree health and economic variables to estimate actual damages. An emerging theme in these studies is that amenity and other non-timber economic values of forests are increasingly at risk of damages from non-native organisms [73]. Because non-market forest ecosystem services have few substitutes relative to timber species, it is anticipated that impacts to non-market forest ecosystem services will incur increasingly severe damages in the future.[6]

Several studies have used spatial general equilibrium models of international trade to simulate the impacts of non-native forest insects and pathogens on domestic timber economies. A scenario in which Asian gypsy and nun moth becomes established and spreads widely in the USA results in estimates of lost revenues to timber producers, plus additional expenditures of timber consumers, of $60 million per year [7]. A similar study of the impacts of the *Nectria* pathogen on the wood products sector in New Zealand concluded that economic losses would range from $1.1–$21.8 million per year [8]. A simulation of the impact on the world forest sector of imposing a gradual ban on round wood exports concluded that consumer expenditures for round wood would increase by 2.2% and producer revenues would increase by 1.9% [6].

Awareness of the impacts of invasive species on the value of non-timber forest ecosystem services is increasing [74] in concert with an emerging body of literature describing economic impacts of biological invasions on non-timber values. Several studies have combined geo-referenced data on non-native forest pest and pathogen outbreaks with economic transactions data and concluded that non-native forest organisms substantially reduce property values in residential forests [75–77], inducing losses ranging up to hundreds of millions of dollars per year [9••]. Damages from non-native forest species also cause homeowners to expend large sums in damage control costs, and predicted control costs associated with the emerald ash borer in the USA could cost homeowners and communities as much as $10.7 billion over 10 years [78].

Several studies have evaluated the impacts of non-native insects and pathogens on the public's willingness-to-pay to protect forest health in public forests [reviewed in [73]]. A major conclusion of these studies has been that while use (e.g., recreational, esthetic) values are substantial, it is essential to also include non-use (existence, bequest, and option) values in estimates of total value. This conclusion was

[5] It has been argued that economic estimates of global damages from invasive insects are "massive but grossly underestimated" [72••].

[6] For example, it has been argued that the timber economic impacts of the chestnut blight were largely mitigated by substitution of alternative species for chestnut used by the wood products industry [1].

recently highlighted in a study of the public's willingness to pay to protect forests in the Great Smoky Mountain National Park (USA) from a non-native forest insect [79]. Results of that study, aggregated across residents of (only) one state, suggest an aggregate willingness to pay exceeding $100 million per year to support a 3-year program in the Park. More recently, the increasing incidence of phytosanitary breaches in the UK has stimulated research into the economic value of protecting native trees and woodlands. The resulting estimates suggest that residents have a substantial willingness to pay for controlling forest diseases [80], and the public value of protecting woodlands in England and Wales from select forest pathogens range from £202–560 million ($250–658 million) per year [81].

While each of these studies contributes a point of reference for cost-benefit analyses of specific forest protection programs, a larger challenge is to understand how individual observations of economic damage contribute to an understanding of future aggregate economic values at risk from non-native forest organisms. Recent efforts demonstrated improved methods for predicting future aggregate economic impacts from multiple biological invasions based on the idea that economic damages are random variables that can be depicted as probabilistic functions [9••]. It was found that the greatest impacts of recent biological invasions in US forests have been largely borne by local governments and residential landowners. In particular, wood-boring insects were found to induce nearly $1.7 billion in annual local government expenditures and approximately $830 million in annual lost residential property values. The risk of similar impacts recurring in the next decade was estimated to be about one-in-three.[7]

Conclusions

Policies focused on preventing the entry and establishment of non-native forest insects and pathogens must address an inherent tension between irreversible sunk costs stemming from economic and political irreversibilities (option values) and failed biosecurity efforts that have led to irreversible ecological and economic impacts (quasi-option values). Our review of policies enacted to enhance the phytosanitary security of forests at national borders suggests that uncertainty regarding the costs and benefits of policy actions has biased decisions towards wait-and-see approaches and the minimization of type I errors (over-regulation). However, growing awareness of the economic costs associated with type II errors (under-regulation) have stimulated calls for greater precaution in approaches to forest phytosanitary protection. Policies with modest sunk costs that are flexible enough to allow reversible actions are likely to be enacted more rapidly. Global collaborations among economists, other social scientists, ecologists, pathologists, and entomologists are urgently needed to identify systems of integrated off-shore and at-the-border interventions (such as sentinel tree programs, improved quarantine measures at invasion hubs and risk-based border inspection procedures) that can efficiently and effectively balance the protection of future forest values with the sunk costs of forest phytosanitary policies.

[7] Timber impacts were typically much smaller, often by orders of magnitude, than impacts on local governments and residential households.

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Compliance with Ethical Standards

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