Pathway-level risk analysis: the net present value of an invasive species policy in the US

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Invasive species policies are often directed at pathways of introduction, yet few analyses have examined risk at the pathway level. We synthesize the best available economic and ecological information surrounding International Standards for Phytosanitary Measures No 15 (ISPM15), a pathway-level international phytosanitary policy for treatment of wood packaging material. We highlight temporal factors for calculation of net benefits, emphasizing that while we cannot stop invasions, even delaying new arrivals results in substantial economic benefits. We show that policy implementation, although costly and yielding only moderate protection, can generate >US$11 billion in cumulative net benefits by 2050, averting the introduction of more pests than currently exist in the US. We also discuss the relative importance of different sources of scientific uncertainty and identify the most crucial data needs. This is the first pathway-level economic risk analysis assessing the current scientific evidence for the net benefits of a phytosanitary policy.

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Globally, invasive species cost billions of dollars annually (Pimentel *et al.* 2005). However, resources are limited and management incurs substantial costs. As such, risk analysis – assessing the probability and magnitude of potential damages as well as the cost effectiveness of management – has been advocated as a means of informing invasive species policies (Lodge *et al.* 2006). To date, most risk analyses have focused on evaluation of single species (Leung *et al.* 2012), which may help reduce *purposeful* introductions of harmful species (eg live animal trade), or prioritize management following establishment. However, to prevent *accidental* introductions, which are byproducts of commerce and include many of the most economically harmful invasions (eg emerald ash borer (*Agrilus planipennis*); Aukema *et al.* 2011), one must manage entire introduction pathways. Thus, pathway-level risk analysis (PLRA) is relevant for many existing or proposed policies (eg Lodge *et al.* 2006). Further, given the substantial costs of such policies (Prestemon *et al.* 2006), economic analyses of their net benefits would be particularly worthwhile.

PLRA is challenging because many species within a pathway have not been studied, and inferences will necessarily be based on statistical aggregates across species. Nevertheless, PLRA should be based on the best information available, as the alternative is to rely solely on expert judgment or to draw inferences from a subset of available information. Indeed, researchers have begun to conduct quantitative analyses at the pathway level, but these remain limited to individual components of risk. For example, Costello *et al.* (2007) examined introductions as a function of trade. Establishment probability based on propagule pressure has been examined for several pathways (Bradie *et al.* 2013; Brockerhoff *et al.* 2014). Estimates exist for the combined damages caused by all pests introduced via a particular pathway (Aukema *et al.* 2011). Finally, studies have considered the economic costs of phytosanitary policies (Prestemon *et al.* 2006; Strutt *et al.* 2013), and the reduction in introductions due to such policies (Bartell and Nair 2004). However, to our knowledge, no study has integrated these components to estimate the net economic benefits of an international invasive species policy.

We developed a PLRA, incorporating 100 years of information on forest insect pest invasions, half a century of data on pest interceptions, estimates of policy effect on establishment rates, integrated models to predict new establishments and damages at the pathway level, and policy-driven changes in economic flows. We also assessed sensitivity to two forms of uncertainty: irreducible (ie stochasticity) and reducible (ie epistemic) uncertainty (eg Olson 2006). This is the first economic PLRA and the first analysis to assess the current scientific evidence for the net benefits of an existing phytosanitary policy.

Methods

Here, we describe the pathway and invasive species policy (International Standards for Phytosanitary Measures No 15 [ISPM15]) and the extension to incorporate uncertainty (see WebPanel 1 for mathematical details). In Figure 1 we illustrate the conceptual model (detailed below) in which the costly implementation of ISPM15 reduces the propagule pressure associated with international trade, which in turn generates benefits from reducing the number of damaging establishments.

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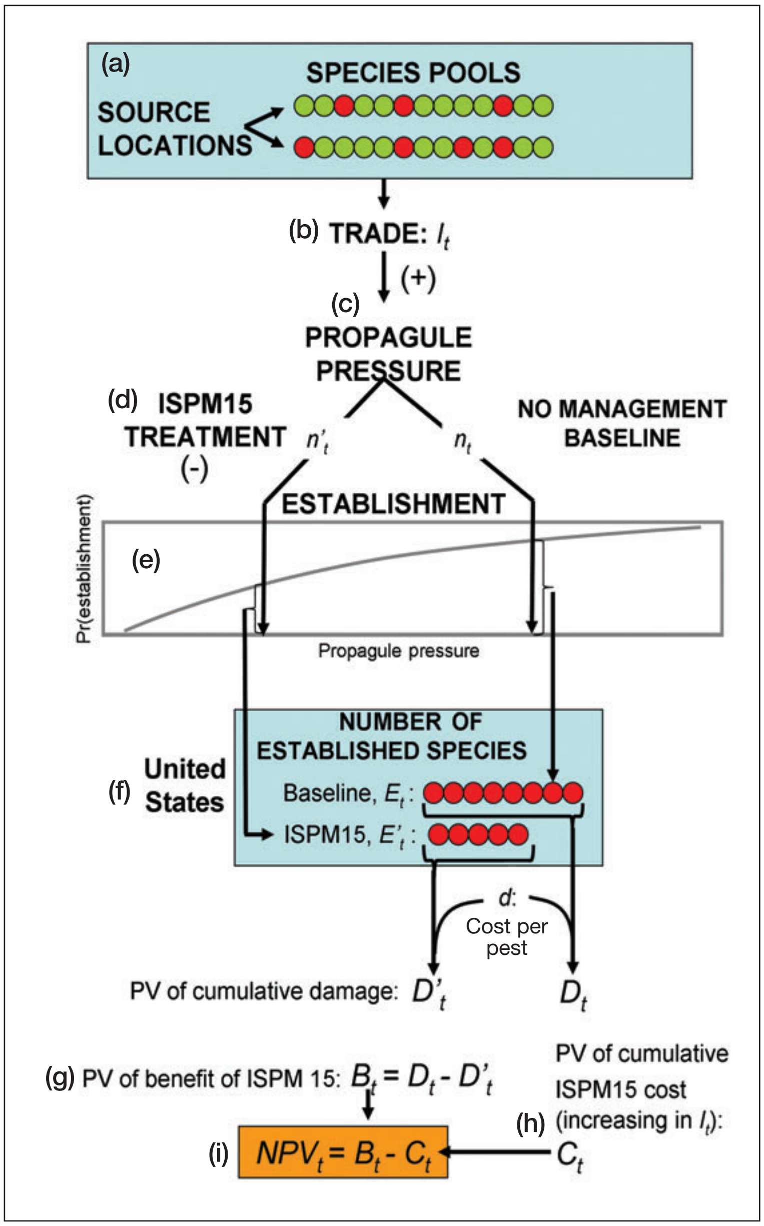

Figure 1. *A conceptual diagram of the model. Dots represent stylized individual species: red denotes species that have established and green denotes the unestablished species pool. As species establish, they exit the unestablished species pool to avoid double counting. Species are transported from source locations via wood packaging material (WPM) through trade imports (I_t). Thus trade, which is forecast to increase over time, increases both propagule pressure (n_t) and the cost of ISPM15 treatment. However, ISPM15 reduces propagule pressure, thereby reducing the probability of establishment for each species, as compared to the baseline. The reduced number of establishments (E'_t) in the US as compared to baseline (E_t) reduces the damages cumulated across time. The cumulative benefit (B_t) of ISPM15 is calculated as the difference in cumulative damages in the absence (D_t) and the presence (D'_t) of ISPM15. The net present value at year t (NPV_t) is calculated as B_t minus the cumulative cost of treatment (C_t), discounted across time (PV = present value). The superscript ' denotes variables under ISPM15 (eg n'_t is propagule pressure given ISPM15). We use subscript t to indicate variables that are time dependent. Bolded letters (a) through (i) correspond to different components described in the text.*

Case study: wood boring pests and ISPM15

We focused on ISPM15 (IPPC 2002) targeting wood packaging material used in international trade (eg crating, pallets). Implemented by more than 70 International Plant Protection Convention signatory countries, ISPM15 addresses a major pathway for introduction of wood borers, which are the most damaging guild of forest insect pests (Aukema *et al.* 2011), in addition to other wood-inhabiting pests such as nematodes and fungi (Brockerhoff *et al.* 2006; Haack 2006).

Of the borers treated by ISPM15, bark (Scolytinae) and longhorned (Cerambycidae) beetles have the best interception records. Thus, Brockerhoff *et al.* (2014) used interceptions of these groups and the simulation extrapolation method (SIMEX; Cook and Stefanski 1994) to fit a model of relative propagule pressure, and also statistically derived a potential invader species pool of 2468 Scolytinae and Cerambycidae species, from the number of non-intercepted establishments. In total, 21 species belonging to Scolytinae and Cerambycidae established in the US from 1909–2008, 18 of which occurred in the interception records (Aukema *et al.* 2010; Brockerhoff *et al.* 2014). Across all borer taxonomic groups, 58 species have established in the US from 1909–2008. To estimate the total species pool across all borer groups, we scaled the number of Scolytinae and Cerambycidae species by the inverse of their share of borer establishments (2468 × [58/21] = 6817 total species pool; Figure 1a).

Model description

Deterministic model

We estimated the benefits and costs of ISPM15 for the US through 2050. This policy involves treating wood packaging material to kill organisms, thereby reducing the numbers introduced into the US (ie propagule pressure) and hence the number of damaging establishments.

We modeled propagule pressure as proportional to imports. This allowed us to project propagule pressure into the future, using changes in imports to scale relative propagule pressure over time, with 1909–2008 as our baseline (henceforth termed our trade-driven propagule pressure model [TPM]; Figure 1b; WebPanel 1). We used historical import data, and then estimated growth in US imports based on projections of US gross domestic product (GDP) (Foure *et al.* 2012) and imports as a share of GDP to 2050.

Not all species have the same propagule pressure. We followed Brockerhoff *et al.* (2014) and used interception data from infested shipments (recorded in the US and New Zealand between 1950 and 2008) as a proxy for the frequency distribution of relative propagule pressure across species (Figure 1c; WebPanel 1). Brockerhoff *et al.* (2014) combined interception records from the US and New Zealand because both datasets describe species with worldwide origins that are moved internationally via wood packaging materials, and the combined dataset enabled us to obtain better estimates for species that occur rarely in this pathway. Species were separated into 11 propagule pressure categories to generate a frequency distribution. We estimated the number of species in each propagule pressure category by multiplying the normalized frequencies by the total species pool (described above; WebPanel 1).

We modeled the management effect as the proportion of propagule pressure averted (*m*; Figure 1d; WebPanel 1). Haack *et al.* (in prep) estimated efficacy of ISPM15 – using interception data from the US Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) Agriculture Quarantine Inspection Monitoring (AQIM) records of random cargo inspections – before and after implementation of ISPM15, and found a 52% decrease in infestations in the interception records (our surrogate for relative propagule pressure).

We modeled the number of establishments (historical and future) as a function of relative propagule pressure (Figure 1e; WebPanel 1). We estimated an establishment coefficient (α; WebPanel 1; Brockerhoff *et al.* 2014) by least squares fitting of the number of observed establishments from 1909–2008. Thus, to estimate baseline establishments (in the absence of ISPM15) we defined a baseline relative propagule pressure, linked it to observed import volume and establishments (1909–2008), and then used forecasted growth in imports to estimate the change in propagule pressure and its consequences for establishments. We modeled depletion of the unestablished species pool by removing the fraction of species in each propagule pressure category that established over time to avoid double counting and because species with high propagule pressure are likely to establish earlier. Averted establishments were then given by the difference in establishments between the baseline scenario (without ISPM15) and the alternative of reduced propagule pressure resulting from ISPM15 (Figure 1f).

To translate reduced establishments to averted damages, we estimated the average annualized cost of a pest based on the statistical approach outlined in Aukema *et al.* (2011). To estimate the frequency distribution of possible damages that might arise from any given establishment, Aukema *et al.* (2011) used observed frequencies of innocuous and moderately damaging pests (those where some evidence of impact exists), and full economic analyses of damages caused by three of the worst pests as data. In our analysis, we included only profit loss to the timber market and loss in property value to home owners, resulting in expected annualized average damage of $34 million (*d*; WebPanel 1; all dollar amounts are expressed in US$). Further, we assumed a lag of 10 years after establishment before species begin to cause damage (Hochberg and Weis 2001; Liebhold and Tobin 2008). The total damages caused by time *t* (D_t) were calculated as the expected pest damage (*d*), multiplied by the number of establishments older than the lag phase, cumulated to time *t* (Figure 1f; WebPanel 1). Thus, the benefit of ISPM15 was calculated as the difference in cumulative damages in the absence (D_t) and presence (D'_t) of ISPM15 (Figure 1g).

The economic cost of implementing ISPM15 (Figure 1h) was modeled as the welfare loss resulting from increased transport costs from treating wood pallets (taken from Strutt *et al.* 2013). We estimated this economic cost using the GTAP-M (Peterson 2006) version of the Global Trade and Analysis Project computable general equilibrium model, which captures international and domestic trade flow adjustments in response to compliance costs. The cost of compliance with the current ISPM15 heat treatment (or fumigation) of $1.50 per pallet was obtained from an e-mail survey of wood packing manufacturers. In GTAP-M, the costs of ISPM15 were operationalized as an increase in transport costs, which affects the prices and quantities of trade and flows endogenously through the economy (Strutt *et al.* 2013). Implementation of ISPM15 was estimated at $437 million, in 2004 dollars. After initial treatment of all pallets, we modified the estimates from Strutt *et al.* (2013) to account for pallet re-use and an average pallet life span of 6 years (Gasol *et al.* 2008). The annual cost was also scaled by the projected increases in imports to 2050 (Foure *et al.* 2012), considering the need for new wood pallets (WebPanel 1). We calculated the net present value (NPV; Figure 1i) of the path of annual net benefits using a 3% discount rate.

Incorporating uncertainty

We used Bayesian statistics to examine the sensitivity of results to epistemic uncertainty in the relationships between propagule pressure and establishment (α), damages (*d*), and the effectiveness of ISPM15 (*m*). Further, we used simulations to examine stochasticity across which species were established and their damage (WebPanel 1). To examine uncertainty in trade-driven propagule pressure, we considered uncertainty in forecasts of imports. We accounted for seven scenarios of US economic growth to 2050, and analyzed the sensitivity of results to the minimum and maximum growth scenarios (Ward 2011; Hawksworth and Chan 2013). Finally, we also allowed for structural uncertainty with respect to damage distributions by considering different families of curves (gamma and power) (Aukema *et al.* 2011) and the propagule pressure model. For the latter, we estimated an alternative model where propagule pressure grows over time at a fixed rate of increase (henceforth termed "constant growth propagule pressure model" or CGPM). For

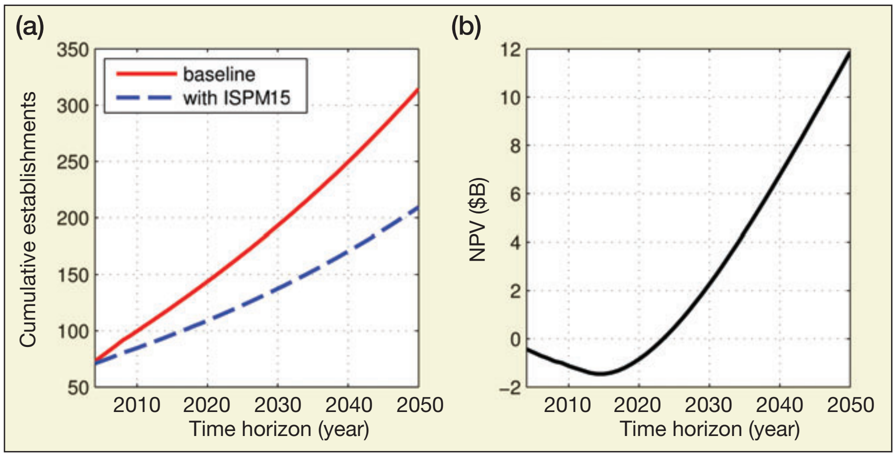

Figure 2. *Deterministic model projections of the number of establishments over time in the US in the presence and absence of ISPM15 (a) and the resulting NPV of implementing ISPM15 (b) as a function of the time horizon considered.*

CGPM, we determined the rate of propagule increase that resulted in the predicted establishments that best-fit the historical decadal establishment records of borer pests over the past 100 years (WebPanel 1).

We conducted 10 000 simulations for each uncertainty scenario, resampling parameter values and regenerating the invasion process to 2050. We calculated mean, median, and 90% quantiles of net benefits over time, and the fraction of simulations where NPV was positive at 2050.

Results and discussion

Our synthesis incorporated economic growth, heterogeneous propagule pressure (Brockerhoff *et al.* 2014), the effectiveness of ISPM15 (Haack *et al.* in prep), estimates of the heterogeneous damages by pests (Aukema *et al.* 2011), and economic cost after adaptation to the policy (Strutt *et al.* 2013). We conducted an extensive analysis of uncertainty and explicitly considered temporal factors – two aspects that happened to be critical to our understanding of the costs and benefits of phytosanitary policy. Indeed, even though most species were innocuous, ISPM15 was only partially effective (52% reduction in propagule pressure) and its estimated initial costs of $437 million were greater than the expected annual damages of a wood borer pest ($34 million); altogether, the policy was worthwhile when cumulative temporal factors were considered.

Temporal factors

We estimated that ISPM15 yields an expected NPV of $11.9 billion when accounting for costs and benefits through 2050. The NPV was positive despite high treatment cost and moderate policy effect, as both the expected number of avoided establishments and the resulting annual damages for each species continued to accumulate over time. Further, although the upfront cost of treating all wood pallets was high (Strutt *et al.* 2013), only a fraction of pallets needed to be replaced annually due to their re-use (Gasol *et al.* 2008). We also incorporated depletion of the unestablished pool of species as establishments accrued and discounting, which placed a decreasing weight on years farther in the future, where relatively large net benefits occurred. Finally, we modeled an increasing volume of trade over time, which drove both increasing costs of treating wood pallets and increasing propagule pressure (higher potential for benefits of averted damages).

Integrating these temporal factors, we found that expected cumulative establishments of pests in the wood pallet pathway grew nearly linearly to 2050 (Figure 2a) but at a lower rate when treated. Under ISPM15 the number of borers in the US could triple from current levels if propagule pressure increases proportionally with projected trade. However, without ISPM15, pest numbers could quadruple. The difference between the baseline and ISPM15 scenarios in the number of establishments was initially small but increased over time. This resulted in a NPV that was negative over a short time horizon, but where expected *annual* benefits were projected to exceed the annual costs by 2016 and the *cumulative* NPV became positive by 2024 (Figure 2b).

Three key insights emerged from these results. First, even with ISPM15, the US should be prepared for substantial increases in forest pests. Second, even though ISPM15 is only partly effective, the number of averted pests through 2050 is substantial, greater than the number of pests currently established in the US. Third, phytosanitary policy is a long-run investment that may generate substantial net benefits that become apparent only over multiple decades (as with policy to reduce carbon emissions).

Uncertainty analyses

Across all sources of uncertainty, our results were most sensitive to the structure of the propagule pressure model (Figure 3). If propagule pressure increases in proportion to imports (TPM; Costello *et al.* 2007), we estimate substantial cumulative net benefits through 2050, whereas if propagule pressure grows exponentially with a constant growth rate (CGPM), we project a net loss. This was reflected in the baseline (without ISPM15) number of establishments (314 and 108 species under the TPM and CGPM, respectively). Likewise, the number of establishments *avoided* by 2050 was also greater for TPM than under CGPM (105 versus 22 species, respectively). We present CGPM as the most conservative estimate of ISPM15 benefits. In this scenario, the cost of ISPM15 increased with

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imports but the benefits were decoupled and did not.

Notably, there was very little difference in NPV between the uncertain economic growth scenarios and the deterministic model using TPM (Figure 3a) despite the large effect on the number of averted pests, which ranged from 87 to 114 (Figure 3c). This was because differences in economic costs were almost entirely balanced by differences in benefits due to averted establishments. For CGPM, of course, there was no effect of trade uncertainty on establishments (Figure 3d); however, trade uncertainty did affect NPV (Figure 3b), because imports were decoupled from establishment but still affected ISPM15 cost.

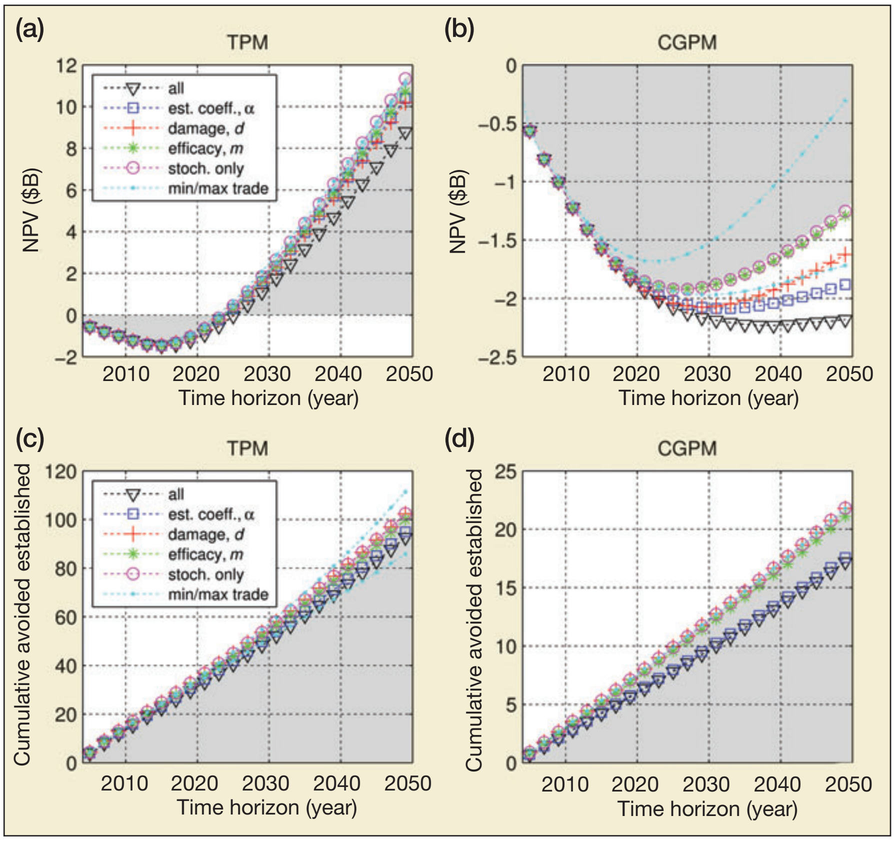

Figure 3. *Estimates of expected NPV (a and b) and cumulative avoided establishments (c and d) under epistemic and/or stochastic uncertainty, as a function of the time horizon, for propagule pressure models based on trade (TPM – [a and c]) and a constant growth rate (CGPM – [b and d]). Deterministic results are depicted by the gray shading.*

Our exploration of uncertainty also revealed several other patterns (Table 1). Stochasticity did not shift the *average* outcomes away from the deterministic estimates presented above, but NPV did range from –$2.0 billion to $33.0 billion (NPV 90% credible interval [CI], based on a 2050 time horizon and the TPM model). For epistemic uncertainty, the widest CI in both avoided establishments and NPV was due to uncertainty about the effectiveness of ISPM15 (m). In contrast, epistemic uncertainty in the establishment coefficient (α) shifted the mean NPV away from the deterministic outcome but had the smallest NPV 90% CI. Finally, even with the TPM model, incorporating all forms of uncertainty, NPV was only positive in 53% of the simulations: sometimes baseline establishments are relatively low, pests do not cause much damage, or treatment is not successful. Thus, the key messages are twofold. First, uncertainty affected both the range of potential outcomes as well as expected values. Second, ISPM15 may be viewed as a form of insurance, which can pay substantial dividends by protecting against severe, albeit uncertain, outcomes.

Future research

The effects of uncertainty in our analysis can guide further research. Structural uncertainty in how propagule pressure changes in the future, and whether this is decoupled from the growth in US imports and the cost of ISPM15, is critical to expected net benefits. For precision, better estimation of ISPM15 effectiveness was most important. To achieve this, we argue that enhanced sampling and recording of interception records would be required. Even though doing so would likely increase inspection costs, we would expect benefits in terms of improved opportunities for management, allocation of effort, and cost–benefit estimation.

It is worthwhile to also develop alternative models in addition to factors we analyzed, given the data and techniques available. Logically, the components involved in single species invasion risk (Leung *et al.* 2012) are also relevant for each species within a pathway. In the future, researchers could consider all individual components of invasions at the pathway level using statistical aggregates to extrapolate across multiple species.

Finally, we were primarily interested in generating an aggregate US estimate, but forthcoming studies could include a broader worldwide analysis or conversely a more finely detailed analysis (eg region of origin, commodity type, or region of introduction). This could potentially be important, for instance, if poor ISPM15 implementation was concentrated in regions with or on commodities of higher risk.

■ Conclusions

The current balance of evidence suggests that an invasive species policy (ISPM15) could be very worthwhile. Integrative studies such as this one are needed to explicitly assess current understanding, identify key data collection and research gaps, and provide the best available evidence for policy. The alternatives are to make arguments based

Table 1. Avoided establishments and NPV through 2050 for both propagule pressure models under uncertainty scenarios

		Avoided establishment		*NPV ($billion)*			
Model	*Uncertainty scenario*	*Avg*	*90% CI*	*Avg*	*90% CI*	*Med*	*NPV > 0*
TPM	all	95.1	(10, 164)	9.2	(–4.8, 41)	0.5	52.9%
	establishment coefficient, α	97.5	(72, 126)	10.9	(–2.5, 32.4)	8.5	85.2%
	damage, *d*	105.1	(89, 121)	10.7	(–4, 44.2)	1.6	60.8%
	efficacy, *m*	102.7	(11, 168)	11.2	(–4.8, 35.9)	8.7	79.3%
	stochastic only	105.2	(89, 122)	11.9	(–2, 33)	9.7	88.8%
	min trade	87.7		11.7			
	max trade	114.7		11.6			
	deterministic	105.1		11.9			
CGPM	all	17.6	(1, 44)	–2.2	(–4.8, 4.7)	–4.6	10.8%
	establishment coefficient, α	18.0	(5, 40)	–1.9	(–4.8, 9.5)	–4.2	20.2%
	damage, *d*	22.3	(15, 30)	–1.6	(–4.8, 6.1)	–4.3	13.5%
	efficacy, *m*	21.6	(2, 37)	–1.2	(–4.8, 10.7)	–3.8	24.5%
	stochastic only	22.3	(15, 30)	–1.2	(–4.8, 10.3)	–3.5	25.1%
	min trade	22.3		–0.2			
	max trade	22.3		–1.7			
	deterministic	22.3		–1.2			

Notes: In the "stochastic only" case, we included no further sources of uncertainty. In the rest, we included the two sources of stochasticity and also each of the four sources of epistemic uncertainty individually in the establishment coefficient (α'), damage (*d*'), and efficacy (*m*') and trade forecast (minimum and maximum) scenarios. α', *d*', and *m*' were estimated using Bayesian statistics, whereas sensitivity analysis was used for trade forecasts. In the "all" scenario, we included the effect of stochasticity and all Bayesian estimates of epistemic uncertainties together. Trade-driven propagule pressure model (TPM), constant growth propagule pressure model (CGPM), Avg (average), CI (credible interval), Med (median).

on single components of the invasion process, or to base analyses not on data but on expert opinion or anecdotal evidence. Although uncertainty will always exist, the appropriate view should be one of continual scientific improvement and development of novel methods and analyses, given the best data available. Thus, the work here provides a new baseline from which to build our understanding of the costs and benefits of invasive species policy.

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