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

Brian Leung^{1*}, Michael R Springborn², James A Turner³, and Eckehard G Brockerhoff^{4,5}

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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lobally, invasive species cost billions of dollars annu-Gally (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 based on 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.). 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') in the US as compared to baseline (E) reduces the damages cumulated across time. The cumulative benefit (B,) of ISPM15 is calculated as the difference in cumulative damages in the absence (D.) and the presence (D'.) of ISPM15. The net present value at year t (NPV.) is calculated as B. minus the cumulative cost of treatment (C_r) , discounted across time (PV = present value). The superscript ' denotes variables under ISPM15 (eg n', 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 $(2468 \times [58/21] =$ 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.* (2014) 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. 2014), 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 B Leung et al.

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-term 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

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.

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 estab-

lishments 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 when we incorporated 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.

20

0

2010

2020 2030

Time horizon (year)

2040

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



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.

2050

0

inspection costs, we would expect benefits in terms of improved opportunities for management, allocation of effort, and cost-benefit estimation.

2010

2020 2030

Time horizon (year)

2040

2050

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

There has recently been controversy over whether it is worthwhile to prevent invasive species, with arguments that most introduced species are innocuous and that management is costly and usually only delays invasions rather than preventing them. However, the current balance of

		Avoided establishment		NPV (\$billion)			
Model	Uncertainty scenario	Avg	90% CI	Avg	90% CI	Med	NPV > 0
ТРМ	all	95.I	(10, 164)	9.2	(-4.8,41)	0.5	52.9%
	establishment coefficient, $lpha$	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			

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

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).

evidence suggests that invasive species policy could be very worthwhile, with net benefits exceeding US\$11 billion for ISPM15 by 2050. 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 on single components of the invasion process, or to base analyses not on data but on expert opinion, intuition, 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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B Leung et al. - Supplemental information

WebPanel 1

We begin by describing the components of a deterministic biological and economic model, which we later extend to incorporate uncertainty. We estimate the net benefits of the policy for the US as given by the difference between expected benefits from reduced establishments and losses as a result of costly treatment measures.

Expected benefits

To calculate benefits we first estimate the expected number of establishments *prevented* by the policy and then characterize expected damages avoided when an establishment is prevented. To represent the establishment process, we model the number of (historical and future) establishments as a function of propagule pressure, which we define here as the number of shipments infested (with a non-native species) that are received in a given period of time. We begin by estimating the baseline (pre-ISPM15) relationship between propagule pressure and establishments, using data on cumulative historical establishments and observed infested shipments. However, projecting the impacts of a policy change forward in time requires that we consider how annual propagule pressure may change over time (eg due to changes in import volume and due to the proportion of shipments that are infested).

Estimating the baseline (pre-ISPM15) relationship between propagule pressure and establishments

Let $N_{t,s}$ represent the true propagule pressure in year *t* for species *s*: that is, the number of individuals of species *s* introduced, either intentionally or unintentionally, to the US via the pathway of interest, wood packaging material (WPM). We assume that the likelihood that a given species has established by year *T* is a function of cumulative

propagule pressure, $N_s = \sum_{t=1}^{T} N_{t,s}$. We also assume that if species *s* has not yet

established, each individual introduced generates a constant probability of establishment, determined by the coefficient A. The probability that species *j* has established by time T is then equal to $1 - e^{-AN_s}$. In aggregate, if there are S species in the pool of potential establishers, then the expected cumulative number of established species by year T, E_T , is

$$E_T = \sum_{s=1}^{S} 1 - e^{-AN_s}$$
 S1

While we do not have measures of true propagule pressure, we use historical data on numbers of interceptions of infested shipments as a proxy for N_s , using records of true bark beetles and longhorned beetles, because substantial interception data are available (see below). We rescale interceptions to focus on a unitless relative metric of propagule pressure: $n_s = N_s / \max(N_1, ..., N_s)$. Thus, equation S1 can be converted to express cumulative establishments by time *T* as a function of relative propagule pressure:

$$E_T = \sum_{s=1}^{S} 1 - e^{-\alpha n_s}$$
 S2

The relationship between nominal and relative propagule pressure is given by $N_s = \lambda n_s$, where λ is an unobserved scaling factor. While λ is not needed for our purposes, if this scaling factor was known it could be used to recover the establishment parameter of the original propagule pressure model (equation S1) according to $\alpha = \lambda A$.

To enable baseline predictions of future establishments (in the absence of ISPM15) using projections of propagule pressure, it is necessary to estimate the parameter α . To inform this estimation we use data on historical establishments and propagule pressure from Brockerhoff et al. (2014). These data include interceptions recorded at US and New Zealand ports of entry for imports. While we focus on modeling the effect of ISPM15 in the US, here we take advantage of the combined US and New Zealand interception record, which enables a richer characterization of the pool of species moved via international trade (described below). Substantial data exist for two groups for which interception records were available: true bark beetles (Scolytinae, records for 107 species) and longhorned beetles (Cerambycidae, records for 261 species). In addition to intercepted species, we estimate the number of species in these taxa that occur in these pathways so rarely that they are unlikely to have been intercepted (1800 non-intercepted longhorned beetle species, and 300 non-intercepted true bark beetle species). In total, Brockerhoff et al. (2014) estimated 2468 species in these two taxonomic groups. Of the species in these two groups, there have been $E_T = 21$ known species established in the US over the T = 100-year period from 1909–2008. Eighteen of these species also appear in the interception records, and the remaining three species are assumed to be part of the non-intercepted species that occur in this pathway.

To mitigate the effect of idiosyncratic measurement error in the species-level data, we follow Brockerhoff *et al.* (2014) in aggregating the species into discrete bins based on their interception frequency indexed by $i \in [1,11]$. For the remainder of the model we replace subscripting by individual species (*s*) with species bin (*i*). Because interception data for any single country can be sparse, we use combined relative propagule pressure data from the US and New Zealand for each species within a bin (following Brockerhoff *et al.* [2014]). We then convert propagule pressure to relative units for each bin *i*, $n_i = N_i / \max(N_1, ..., N_{11})$. The cumulative establishment equation above can then be expressed as

$$E_T = \sum_{i=1}^{11} f_i (1 - e^{-\alpha n_i})$$
 S3

where f_i represents the number of species in species bin *i* for our two initial taxonomic groups. Using least squares, we estimate that the establishment rate per relative unit of propagule pressure is $\hat{\alpha} = 2.3$. This parameter determines how an increase in the relative propagule pressure for bin <u>i</u> affects the average probability of establishment for species within bin *i*.

To consider establishments by all taxonomic groups in our pathway – not just the two for which high-quality interception data exist – we assume that the statistics for true

bark beetles and longhorned beetles are representative of all other relevant taxonomic groups in the pathway. More specifically, we assume that the distribution of propagule pressures was similar between groups, and that the per-propagule probability of establishment was likewise similar. To calculate f_i we use the observed total number of establishments across all taxonomic groups (E = 58 observed between 1909 to 2008, data taken Aukema *et al.* [2010] and Brockerhoff *et al.* [2014]). We scale the number of bark and longhorned beetle species by the number of establishments in all groups for the US divided by the number of bark and longhorned beetle establishments (58/21). Summed across all propagule pressure bins *i*, this results in 6817 total species (= 2468 × [58/21]).

Projecting baseline future propagule pressure

Because our goal is to project establishments with and without ISPM15 through 2050, we first construct projections of baseline propagule pressure (in the absence of ISPM15). To describe these dynamics, let $n_{i,t}$ represent the relative propagule pressure for species bin *i* in year *t*. We assume that this variable can be decomposed into the product of two terms, $n_{i,t} = n_i n_t$, where n_i represents the relative propagule pressure for each bin (as defined above) and n_t represents the relative propagule pressure from the 100-year record

available for 1909–2008 (*N_i*) that occurs in year *t*. This implies that $\sum_{t=1909}^{T=2008} n_t = 1$. Since

estimation of the relative allocation of propagule pressure between bins, n_i , is already described above, to determine how propagule pressure grows, we need to project n_t into the future.

Base model: trade-driven propagule pressure model (TPM)

For our base model we assume that propagule pressure is proportional to the volume of imports. Projecting forward using this trade-driven propagule pressure model (TPM) requires estimates of future import volume. To estimate future imports we use reported US imports, I_t , from 1908 to 2012 and then estimate growth in US imports from 2012 onward. Projections of US imports are based on projections of US GDP, Y_t , to 2050 from Foure *et al.* (2012) and assume a continuation of the historical linear trend in the ratio of US imports to GDP (World Bank 2013). In the 50 years from 1960 to 2010, the value of US imports as a percentage of GDP grew from 4.4% to 16.3% (World Bank 2013). Assuming continuation of this trend, the percentage would grow to 26.9% by 2050. This is still a smaller percentage than that observed for the UK (32.7%) in 2010. This ensures that projected imports are consistent with the forecast US GDP used to project expected trade costs of ISPM15 to 2050 (see below). Converting trade projections to relative

propagule pressure units, we obtain $n_t = \frac{I_t}{\frac{2008}{\sum_{u=1909}}I_u}$. We then use n_t to calculate the

cumulative number of establishments over time:

$$E_T = \sum_{i=1}^{11} f_i (1 - e^{-\alpha n_i \sum_{t=1909}^{T} n_t})$$
 S4

The term $(e^{-\alpha n_i \sum_{t=1909}^{i} n_t})$ will go to zero over extremely long time horizons, as propagules (n_t) accumulate. This models depletion of the unestablished species pool, and avoids double counting invasions. The maximum number of establishments is therefore the number of species in the pool f_i . Furthermore, this avoids overestimating the rate of establishment, because propagule pressure categories (i) with higher n_i values would be more probable to establish, and would be depleted earlier.

Forecasting the reduction in establishments due to ISPM15

Let $m_t \in [0,1]$ represent the efficacy of the sanitary measure (ISPM15) in year *t*, in terms of the proportion of relative propagule pressure averted. A recent estimate of m_t from available data on reductions in infestation rates is 0.52, drawn from an analysis by Haack *et al.* (in press) of USDA Animal and Plant Health Inspection Service (APHIS) Agriculture Quarantine Inspection Monitoring (AQIM) records of random cargo inspections of shipments with WPM recorded for the US fiscal years (October to September) 2004–2009. AQIM data were collected before and after the implementation of ISPM15, with data collected specifically on WPM beginning in 2004, including recording whether or not WPM was marked with the ISPM15 logo indicating phytosanitary treatment.

Relative propagule pressure after treatment is then:

$$n'_t = (1 - m_t)n_t$$

S5

The expected number of establishments under ISPM15 is given by replacing n_t in equation S4 with n'_t from equation S5. We note that the estimates of ISPM15 effectiveness should be viewed as a lower bound, because some voluntary treatment may have already begun before ISPM15 implementation (thereby reducing the apparent difference pre- and post-ISPM15), and because our proxy for propagule pressure was infested shipments (ie the number of individuals within an infested shipment might be reduced).

Estimating the present value of averted damages

To translate reduced establishments to averted monetary damages, we used estimates for the average annual cost of a pest (d), based on the frequency distribution of damages across wood boring pests (Aukema *et al.* 2011; termed cost-curves previously, but more accurately termed damage distribution here). We adjust from 2009 dollars to 2004 dollars using the US consumer price index

(http://inflationdata.com/Inflation/Consumer_Price_Index/HistoricalCPI.aspx?reloaded=t rue). We include only deadweight losses to the timber market and home owners. We treat parameter values as point estimates using the posterior means of the damage distribution parameters, taken from Aukema *et al.* (2011). We re-calculate the expected damage because Aukema *et al.* (2011) reported the cumulative damage estimates up to the maximum of the current most damaging pest to date. However, forecasting into the future, we consider the possibility and costs of more damaging pests than currently occur, and we therefore integrate under the entire damage distribution.

To begin, we use a deterministic version, the most likely damage distribution (the power function), and the mean parameter values obtained from Aukema *et al.* (2011) (we

explore models with uncertainty below). Further, we assume that there is a lag phase of L periods after establishment before species begin to cause damage. Thus, the number of species causing damage by period t is given by E_{t-L} . To identify the present value of benefits and costs that accrue over the projected future, we discount future values at the rate r, beginning at the year of ISPM15 implementation in 2004 for simplicity. The present value of averted damages from any time t periods into the future is

$$D_{t} = \frac{D_{t} = 0}{\left(1 + r\right)^{t-2004}} \begin{cases} t < L \\ t \ge L \end{cases}$$
 S6

The present value of the stream of benefits from applying the phytosanitary policy ISPM15 over years t = 2004 through τ is

$$B_{\tau} = \sum_{t=2004}^{\tau} D_{t} - D'_{t} .$$
 S7

where B_t is the cumulative benefits and D_t and D'_t are the expected damages without and with ISPM15, respectively.

Expected costs

The economic cost of ISPM15 represents the US economy-wide change in welfare due to increased transport costs arising from the higher cost of wood pallets associated with the need to treat pallets to meet the ISPM15 standard (Strutt *et al.* 2013). The measure of welfare change used is US consumers' willingness to pay to avoid the price effects of the policy (Hertel 1997), an economic metric known as *equivalent variation*. This economic cost, modeled by the domestic margin inclusive version of the computable general equilibrium Global Trade and Analysis Project (GTAP-M) model and database, was estimated at \$437 million (in 2004 dollars; Strutt *et al.* 2013).

As with propagule pressure, we assume that the number of new pallets requiring treatment under ISPM15 increases proportionally with trade projected over a time horizon of 2004–2050 ($\tau = 47$ years). Further, wooden pallets are typically reused over 6 years on average (Gasol *et al.* 2008). For each subsequent year after initial treatment in 2004, we therefore determine the number of pallets requiring treatment by dividing the existing pallets by the average life span of each pallet, *u*, and adding the new pallets required due to increased volumes of trade (I_t). We then treat this as a proportional cost of the \$437 million (\$437*M*) associated with treating all wood pallets in 2004.

$$c_{t} = \$437M * Z_{t}$$

$$Z_{2004} = 1$$

$$Z_{t>2004} = \frac{(I_{t} - I_{t-1} + I_{t-1} / u)}{I_{2004}}$$
S8

We then apply a discount rate (r), as applied to benefits above, to determine the present value of the projected costs of ISPM15:

$$C_{\tau} = \sum_{t=2004}^{\tau} \frac{C_t}{(1-r)^{t-2004}}$$
 S9

Having thus characterized the present value of costs (C_{τ}) above and benefits (B_{τ}), the net present value (NPV) of the policy over a time horizon of τ years is given by

$$NPV_{\tau} = B_{\tau} - C_{\tau}$$
 S10

Incorporating uncertainty

We examine five sources of uncertainty: projections for future transport (ie propagule pressure), epistemic uncertainty in the risk of establishment, the damages due to insect pests, the effectiveness of ISPM15, and stochasticity.

We considered uncertainty in propagule pressure in two ways. First, we took the range of projected growth in trade from seven economic models from five separate studies (Duval and de la Maisonneuve 2010; Hawksworth and Tiwari 2011; Ward 2011; Foure *et al.* 2012; Hawksworth and Chan 2013), and examined sensitivity to the upper and lower projected imports. Additionally, we considered an entire level of structural uncertainty in our propagule pressure model, where transport is not proportional to trade, but instead is determined phenomenologically. We assume a constant exponential growth in propagule pressure (henceforth termed our CGPM model) that results in the best fit to the observed decadal number of establishments between 1909–2008. We assume that propagule pressure in raw units grows over time at a fixed rate γ : $N_t = b \exp(\gamma t)$.

Converting to relative units, **b** cancels and we have $n_t = \frac{\exp(\chi t)}{\sum_{t=1909}^{2008} \exp(\chi t)}$. To estimate the

propagule pressure growth rate, γ , we use values calculated above (f_i, n_i, α) , and

determine the value of γ that would best fit data on cumulative decadal establishments over time E_t , using equation S4. We note that this is likely an underestimate, given that the phenomenological pattern incorporates historical policies and improvements, and because the cost is modeled as increasing proportional to trade, whereas the benefits are decoupled from trade.

To incorporate the other sources of epistemic parameter uncertainty, we had raw data available and could apply Bayesian statistics. We estimated epistemic uncertainty for α , which incorporates both the relation between propagule pressure and interceptions, and the per-propagule probability of establishment and the uncertainty in damages caused. For each α , the propagule pressure models were also re-fit (equations S2–S4). We use the following Bayesian formulation:

$$\pi(\alpha \mid X) \propto pr(X \mid \alpha) * pr(\alpha)$$

$$pr(X \mid \alpha) = \prod_{j=1}^{J} (1 - e^{-\alpha n_j}) \prod_{k=1}^{K} e^{-\alpha n_k},$$
S11

where $\pi(\alpha \mid X)$ is the posterior probability of the parameter α given the data *X*. *X* comprises both the interception records for true bark beetles and longhorned beetles converted to relative propagule pressures (*n*), as well as the establishment records for all species within these 2 taxonomic groups. $pr(\alpha)$ is the prior probability of α , for which we use a flat prior. $pr(X \mid \alpha)$ is equal to the joint product of all observations, including the *J* species that have established, where we use the probability of establishment $(1 - e^{-\alpha n_j})$, and the *K* species that did not become established, where we use the probability of remaining unestablished ($e^{-\alpha n_k}$). We use Markov chain Monte Carlo methods to estimate the posterior probability distribution, using a chain length of 1 000 000 and a burn in period of 5000.

We also examine epistemic uncertainty in the damage distribution using the Bayesian procedures described in Aukema *et al.* (2011). First, to account for structural uncertainty, we randomly select the damage distribution model proportional to their relative probabilities of being the correct model:

$$pr(M_i \mid X) = \frac{pr(X \mid M_i) * pr(M_i)}{\sum_{i} pr(X \mid M_i) * pr(M_i)}$$
S12

where $pr(M_i/X)$ is the probability of model *i* given the data *X* (in this case, the damage estimate of the poster pest, and the frequencies of innocuous and intermediate damaging pests; Aukema *et al.* 2011). The models (*M*) are the damage distributions, and we assume a uniform prior on each model, such that the priors cancel out. We examine gamma and power distributions as our damage models. Log-normal and Weibull distributions examined in Aukema *et al.* (2011) are not considered here since the expected value is higher than realistically possible. This was not an issue in Aukema *et al.* (2011), because they truncated the distribution at the highest damaging pest, and therefore outcomes were robust and reasonable. After choosing the structural damage distribution model, we randomly sample parameter values from the appropriate posterior distributions.

To examine epistemic uncertainty in the effectiveness of ISPM15, we model uncertainty over the true pre- and post-treatment infestation rates using a Bayesian approach. We begin with a uniform prior distribution describing beliefs over each treatment rate. These priors are updated using data on the number of inspections and interceptions, in either the pre- or post-ISPM15 era. Infestation of each shipment is modeled as a random Bernoulli trial. Given a uniform prior and observations of Bernoulli trials, posterior beliefs on the true infestation rate (either pre- or post-ISPM15) are given by a beta distribution (Gelman *et al.* 2004). Random draws for m_T are generated by taking random draws from the posterior distributions for pre- and post-ISPM15 infestation rates. We assume that ISPM15 would not result in increased propagule pressure, and therefore if $m_T < 0$, we set $m_T = 0$. Finally, we incorporate stochasticity in two ways: which species establishes and what damage it causes. We assign each of the 6817 species in the pool a propagule pressure and level of damage, randomly choosing propagule pressures based on their relative frequency of occurrence ($f_i / \sum_{j=1}^{11} f_j$; equation S3), and damages based on the

cost-curves described above. We assume that propagule pressure is uncorrelated with the magnitude of damages. However, because we examine two different cost categories (lost housing values and lost timber values), we order the magnitude of damages such that highly damaging pests in one category were also highly damaging in the other category.

In each period of the simulation, each species not previously established is allowed the opportunity to establish according to a Bernoulli trial based on their propagule pressure ($E_{i,t} = 1 - e^{-cm_{i,t}}$). If introduction occurs, then species *i* is removed from the unestablished pool and placed in the established pool in year *t*. Thus, we model depletion of the unestablished species pool. Once establishment occurs, we assume that damages accrue after a time lag (*L*; equation S6), and then annualized damages are attributed to each given species. Thus, rather than using expected values, we use stochastic realizations of both establishments and damages. These are then inserted into equations S6–S10 to calculate the net benefits for a given iteration.

We repeat this procedure over 10 000 iterations, regenerating the invasion process to 2050 for each iteration. The outcomes of interest include the time-trajectory of cumulative establishments, benefits, and costs. Simulations are aggregated to calculate the mean, median, and 90% quantiles for environmental (number of establishments) and economic (costs and benefits) variables.

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