Risk assessment for invasive species produces net bioeconomic benefits

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International commerce in live organisms presents a policy challenge for trade globalization; sales of live organisms create wealth, but some nonindigenous species cause harm. To reduce damage, some countries have implemented species screening to limit the introduction of damaging species. Adoption of new risk assessment (RA) technologies has been slowed, however, by concerns that RA accuracy remains insufficient to produce positive net economic benefits. This concern arises because only a small proportion of all introduced species escape, spread, and cause harm (i.e., become invasive), so a RA will exclude many noninvasive species (which provide a net economic benefit) for every invasive species correctly identified. Here, we develop a simple cost:benefit bioeconomic framework to quantify the net benefits from applying species prescreening. Because invasive species are rarely eradicated, and their damages must therefore be borne for long periods, we have projected the value of RA over a suitable range of policy time horizons (10–500 years). We apply the model to the Australian plant quarantine program and show that this RA program produces positive net economic benefits over the range of reasonable assumptions. Because we use low estimates of the financial damage caused by invasive species and high estimates of the value of species in the ornamental trade, our results underestimate the net benefit of the Australian plant quarantine program. In addition, because plants have relatively low rates of invasion, applying screening protocols to animals would likely demonstrate even greater benefits.

invasion pathways | species screening | economics | quarantine | cost–benefit

Whenever accuracy of predictions is <100%, the value of predictions declines as the frequency of the event being predicted declines. This is known as the "base-rate effect," and it occurs because the number of false positives (i.e., nonevents predicted to be events) may far outweigh the number of true positives (i.e., correct predictions that an event will occur). Thus, for events as rare as earthquakes and climatic extremes, it is often rational to ignore predictions altogether to avoid wasting resources preparing for an event that is extremely unlikely to happen (1). Because some previous studies suggested that only a small proportion of introduced nonindigenous species spread and cause harm (i.e., introduced species become invasive at a low base rate), some authors have argued that attempts to predict the identity of invaders are likely to be too inaccurate to be worthwhile (2, 3).

If only a small proportion of introduced species are invasive, a risk assessment (RA) with given error rate will misclassify and exclude many noninvasive species for every invasive species whose introduction it prevents. This may explain why the vast majority of countries have not mandated risk analysis for nonindigenous species introductions, even though such programs are in place for actions that produce comparable environmental risks (ref. 4; e.g., pollution) and even though such policies would clearly produce environmental benefits by excluding many invaders. Two recent advances, however, make it timely to reexamine the concern that the base-rate effect negates the usefulness of RA and border controls for invasive species.

First, new results show that base rates of invasion are often higher than previously reported (5). Second, recently developed tools for determining the identity of species that will become invasive have been applied to diverse regions and taxonomic groups with high accuracy rates (typically 80–95%), e.g., fish in the Laurentian Great Lakes (6); fish in California (7); plants in Australia (8), New Zealand (9), and the U.S. (10, 11); and birds in New Zealand (12).

Here, we develop a bioeconomic framework to identify the specific conditions under which RA and border controls produce greater net economic benefits than a policy under which all species proposed for import are allowed. It is assumed that both the cost of RA and the probability of correctly determining whether a species will be invasive are equal for each species assessed. Only species that are assessed as noninvasive are allowed for introduction. We apply this framework to the Australian ornamental plant industry. Because the benefits and costs associated with introduced species are generally poorly resolved, our model variables are simple enough that data are available. This framework is consistent with the need for greater economic analysis of policies that address environmental problems (13) and constitutes a rigorous bioeconomic evaluation of a species screening protocol.

A nation incurs economic and environmental gains and losses from allowing the importation of nonindigenous species (14, 15). Benefits come from the economic activity species generate (i.e., sales of the species themselves and associated supplies and services). Losses arise because some fraction of introduced species become invasive, causing impacts such as decreased agricultural yield (16), biodiversity losses (17), and increased spending on pesticides and herbicides. Examples of ornamental plants that have become invasive in Australia are Athel pine (*Tamarix aphylla*), which has changed hydrology by displacing native Eucalypt trees along riverbanks (18), and water hyacinth (*Eichornia crassipes*), an aquatic plant that excludes native species and reduces recreation and navigation opportunities by growing in thick mats on the water surface (18). In our model, we assume that the decision to import a species is irreversible (*sensu* Viscusi; ref. 19), because stopping trade in a species that is already introduced and widely distributed will not eradicate it or remove its current or future impacts (benefits and costs), and because eradication of invasive species is generally impossible (20).

Let the annual expected benefit (B_N) from allowing the importation of θ new species be:

$$B_N = \theta V_T, \quad [1]$$

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Abbreviations: NPV, net present value; RA, risk assessment.

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where V_T is the annual benefit generated by trade in a single species. The associated annual expected loss (C_N) incurred by importing the same θ species is given by

$$C_N = \alpha\theta V_I, \quad [2]$$

where α is the base rate of invasion (= no. of invaders introduced/total no. of species introduced), and V_I is the annual economic loss caused by an invasive species. Hence, the annual expected net benefit (E_N) of allowing the introduction of θ species is

$$E_N = \theta V_T - \alpha\theta V_I. \quad [3]$$

When a RA with proportional accuracy A is used, the annual expected benefit (B_R) from the θ species originally proposed for introduction becomes

$$B_R = ((1-\alpha)\theta A + \alpha\theta(1-A))V_T. \quad [4]$$

Eq. **4** accounts for all correctly identified noninvaders and all incorrectly identified invaders having a positive value for trade. Note that, although invasive species cause economic losses (by definition), we have also accounted for their benefits to trade. Invasive species misidentified as harmless cause annual costs (C_R)

$$C_R = \alpha\theta(1-A)V_I. \quad [5]$$

Including a fixed annual cost of administering the RA (D), the annual expected net benefit from using RA (E_R) is

$$E_R = ((1-\alpha)\theta A + \alpha\theta(1-A))V_T - \alpha\theta(1-A)V_I - D. \quad [6]$$

Assuming the annual flow (Eq. **6**) is repeated each year, we simulate costs and benefits into the future. To do this, an appropriate annual discount rate must be used to account for the decreased value placed on future events compared with events that occur in the present. After substantial debate over appropriate values for discount rates, it is now widely acknowledged that the rate used should match the process being modeled (21). Efforts to prevent the introduction of invasive species are similar to reducing greenhouse gas emissions to mitigate global warming; both represent attempts to prevent long-term environmental problems, and for both there is considerable uncertainty around predictions of impact and thus a high potential for surprise. A previous study took the results from a survey of 2,160 economists' opinions about the appropriate discount rate to apply to assessments of global warming and aggregated these into a gamma distribution such that the discount rate declines over time, commonly known as hyperbolic discounting (21). We have used this discount process, which declines from 4% at year 1 to 1% at year 76 and thereafter (see *Methods*). These values are similar to those recommended by economists for similar problems (22–24). In addition, we have performed a sensitivity analysis over a range of constant discount rates (3%, 6%, and 9%) typically used in other economic models. We present results for both hyperbolic discounting and a 3% constant discount rate here; results for discount rates of 6% and 9% are presented in supporting information (SI) Figs. 3–7.

Projecting our models as alternative policy options also requires the use of appropriate values for two lag times: (*i*) the time it takes an imported species to reach retailers and (*ii*) the time it takes an imported invasive species to begin causing economic deficits. According to industry practices and invasion timelines, these benefits and costs were incrementally added over 10 and 50 years, respectively (see *Methods*).

Thus, in our simulations, the costs and benefits from introducing nonindigenous species accrue incrementally over reasonable time

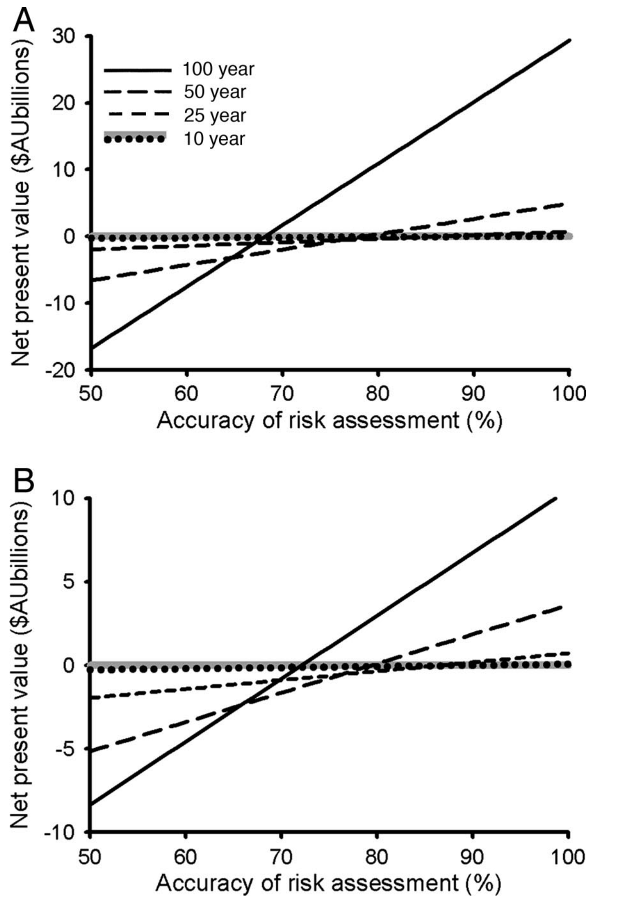

Fig. 1. NPV of RA to the Australian ornamental plants trade for RAs with accuracies from 50% to 100%. *A* was calculated by using a hyperbolic discount rate, and *B* using a fixed discount rate of 3%. Each curve represents the net economic benefits from plants introduced by using RA (of specified accuracy) minus the net benefits under a no-RA policy for time horizons of 100 (solid line), 50 (long dash line), 25 (short dash line), and 10 (dotted line) years. The invasion base rate for the Australian ornamental plants trade (5.39%) is used. Gray line is at zero net benefits, and in *A* (hyperbolic discount rate) is crossed at 69% by the 100-, 78% by the 50-, 87% by the 25-, and 90% by the 10-year line. In *B* (3% discount rate), the gray line is crossed at 72% by the 100-, 79% by the 50-, 87% by the 25-, and 91% by the 10-year line. See *Methods* for further details of discounting and lag times. Note different vertical scales.

periods. Incorporating a discount rate and reasonable lag times, Eqs. **3** (no species screening) and **6** (includes species screening) are projected into the future as alternative policies and used to calculate whether RA will produce positive expected net economic benefits. Here the model is implemented for the Australian ornamental plant industry. We chose this case study, because Australia has required since 1997 that all new plant introductions be screened for likelihood of invasiveness, and because many of the data required for our analysis are already published.

Results and Discussion

We first calculated the expected net present value (NPV) of applying RA over different policy time horizons (Fig. 1). The calculations consider only future species introductions, i.e., the costs and benefits of species already in Australia are not included in the projections of future costs. Over short time horizons, there is not a large difference in NPV between a policy of RA and a policy of no RA for either hyperbolic (Fig. 1*A*) or 3% discounting (Fig. 1*B*). However, for longer periods, RA generates large positive values, with these values depending on the discount rate adopted (compare Fig. 1 and SI Figs. 3 and 4). Because the annual economic costs from invasive species will be borne for long time periods (i.e., invasive species are rarely eradicated), planning horizons of 50–100 years are reasonable, even though this is considerably longer than the planning horizons of most policy makers who face significantly shorter political time horizons. Hence applying RAs with accuracies as low as 69–79% may represent rational policy, depending on the discount rate used. For a RA with ≥90% accuracy, more typical of recent RA tools (6, 8, 10), and the hyperbolic discount rate, implementation is economically beneficial for planning horizons as short as 14 years. We note that for all discount rates tested, including 6% and 9% (SI Figs. 3 and 4, respectively), it is worthwhile to apply a RA with 90% accuracy over time periods ≥15 years. We also note that, because invasive species are rarely eradicated, it would be rational to consider for each time horizon the costs of introduced invasive species much further into the future. Although we have not calculated our model in this way, to do so would increase the NPV of RA for all time periods and all discount rates.

Additionally, we have projected a policy of RA sufficiently far into the future, so that NPV stabilizes (SI Fig. 5). The point at which this occurs depends on discount rate and ranges from ≈100 (9% discount rate) to 450 years (hyperbolic discount rate). NPV at these time horizons represents the total benefits from RA and provides a benchmark against which to compare the more myopic policy options discussed above. The long-term results do not change the conclusions with regard to the benefits of RA, however, because most policy makers work on the shorter time horizons discussed above.

To investigate the sensitivity of the results to the base-rate of invasion, expected net present values were calculated for base rates ranging from 0% to 10% over different time horizons (Fig. 2). Accuracy of RA was assumed to be 90%, a value similar to the accuracies of recent RAs (6, 8, 10). Our results show that, for policy time horizons of 50 and 100 years and hyperbolic discounting, it is worth applying RA if base rates exceed 2.3% and 1.3%, respectively (Fig. 2*A*). This result changed only slightly when discount rates of 3% (Fig. 2*B*), 6%, and 9% are used (SI Figs. 6 and 7, respectively). Assuming that the base rate of invasion in Australia (5.39%) is typical of plant introductions elsewhere, RA would be economically beneficial to many other countries. Again, choice of discount rate has a large effect on the magnitude of the expected value of applying RA (compare Fig. 2 and SI Figs. 6 and 7).

For several reasons, these results underestimate the true net economic benefits from the Australian RA program for plants. First, our estimates of annual cost per invasive species do not include the nonmarket costs of invasive species. These additional costs include loss of biodiversity, citizen time spent volunteering to pull weeds, and lost recreation opportunities (e.g., restricted boating and swimming from water hyacinth overgrowing a lake). We also have not considered the costs arising when diseases are introduced with nonindigenous species. Recent examples of this are the spread in Europe and North America of sudden oak death (*Phytophthera ramorum*) on nursery stock (25) and the introduction of monkeypox virus to the U.S. with an infected Gambian rat, which resulted in 72 human infections (26). The inclusion of such additional costs would lead our calculated net benefits to be much greater.

Second, our estimates of annual benefit per species are high. A compensatory increase in spending on native plants would certainly occur if nonindigenous species were removed from commerce, but this is not included in our model. If we assume, for example, that the total annual value of the Australian ornamental plant industry would shrink by 40% (as opposed to the 64.6% assumed in our analysis; see *Methods*), it would be economically rational to apply RAs with accuracies of just 68% and 56%, respectively, for 50- and 100-year policy time horizons if hyperbolic discounting is used. These figures are 69% and 61%, respectively, for a constant 3% discount rate. More accurate estimates of costs and benefits would, therefore, reduce the accuracy of RA required and lower the minimum base-rate threshold for RA to produce greater economic benefits than no RA.

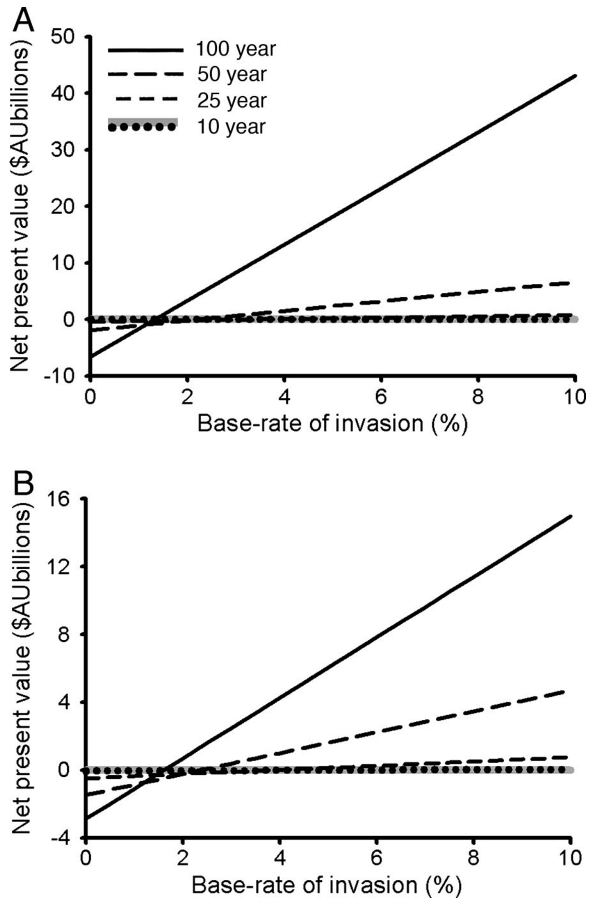

Fig. 2. NPV of RA to the Australian ornamental plants trade for base rates from 0% to 10%. *A* was calculated by using a hyperbolic discount rate and *B* by using a fixed discount rate of 3%. Each curve represents the net economic benefits from plants introduced using RA (of 90% accuracy) minus the net benefits under a no-RA policy for time horizons of 100 (solid line), 50 (long dash line), 25 (short dash line), and 10 (dotted line) years. Gray line is at zero net benefits and in *A* (hyperbolic discount rate) is crossed at 1.3% by the 100-, 2.3% by the 50-, 4% by the 25-, and at 5.7% by the 10-year line. In *B* (3% discount rate), the gray line is crossed at 1.6% by the 100-, at 2.4% by the 50-, at 4.0% by the 25-, and at 5.7% by the 10-year line. See *Methods* for further details of discounting and lag times. Note different vertical scales.

Finally, although data are not available to parameterize the distribution of costs from invasive plants in Australia, we note that the distribution is likely to include many species with relatively low costs and few species with high costs. Policy makers who weigh the worst-case scenario more heavily in their decision making will thus gain more support for the use of RA than our analysis indicates, because the use of RA will protect them from the rare extremely damaging species.

Thus, our results demonstrate strongly that the existing accuracy of RAs makes it economically beneficial to screen plant species for invasiveness before they are introduced to the Australian ornamental industry. Such conclusions are likely to apply in all countries and even more strongly for other taxa, many of which have shorter lag times to invasion and higher base rates of invasiveness. Plants have longer lag times to invasion than, for example, vertebrates (5, 27) and diseases, the latter of which can cause enormous impacts soon after introduction (28). For these taxa, the onset of costs of invasiveness would be earlier, whereas the timing of benefits would likely not change or in the case of diseases would be absent. The net present value from RA would therefore be greater. Base rates of invasion for many combinations of taxonomic groups and vectors of introduction are also higher than for the Australian ornamental plant industry (e.g., fish and mammals introduced to North America from Europe have base rates of invasion of 25% and 62%, respectively; see ref. 5), further increasing the value of RA for these taxa (29).

Within a policy of RA, it may also be rational to concentrate screening efforts on species being transported from new regions or in new trades. All else being equal, these species will present a greater risk, because they have not previously been introduced. Additionally, a number of other approaches to managing the risk of invasion without unduly impeding trade have been proposed. These include controlling the conditions and location of sale for potentially harmful species (14) and the use of tariffs to internalize invasion costs to the industries that benefit from trade in nonindigenous species (30). Although these considerations are not included in our model, their incorporation in policy decisions would likely increase the net value to be derived from trades in live nonindigenous organisms.

The growth of international trade has been accompanied by a worldwide increase in the number of invasive species (31). Until recently, most nations have accepted these as unwanted but apparently unavoidable byproducts of globalization, with only Australia and New Zealand mandating RA for nonindigenous plants and excluding species identified as high risk. However, because many high-risk species are intentionally introduced (e.g., pets, ornamental plants, and aquacultural and agricultural species), accurate risk-assessment tools would make it possible for many other countries to maintain trade near its current trajectory while excluding most harmful species.

For example, the U.S. Department of Agriculture is currently considering amendments to quarantine regulations that would mandate invasiveness screening for all proposed plant introductions, and legislation is pending in the U.S. Congress to institute such screening for all aquatic organisms proposed for introduction. Our analysis demonstrates that, if enacted, each of these is likely to produce net economic benefits in addition to the obvious environmental benefits. Finally, we note that the World Trade Organization mandates through its Sanitary and Phytosanitary Agreement that any risk-reduction strategies applied to imports of nonindigenous species produce net economic gains (32). Our results are a rigorous bioeconomic analysis of a species-screening system, and they clearly demonstrate that RA for nonindigenous species produces net economic benefits.

Methods

Data. An average of 260 plants per year were proposed for introduction to Australia in the period 1997–2002 (33). This value is used as a constant annual rate for all calculations. Overall, 25,360 nonindigenous plant species have been introduced to Australia for use in the ornamental trade (34). Of these, 1,366 have become invasive (34), giving a base rate of invasion of 5.39%, assumed to remain constant over time.

Plants introduced by the ornamental trade account for 70% of all invasive plant species in Australia (34). The best available estimate, although explicitly conservative, of the total annual economic losses caused by invasive plants in Australia is $4.039 billion [in Australian dollars (35); henceforth, all dollar values are Australian]. We thus estimate the cost of invasive plants introduced by the ornamental industry as 70% of this value, or $2.8 billion. Data are not available to determine the individual costs of invasive species introduced for different purposes, and we thus use this as an unbiased estimate of the annual cost of invasive plants that were introduced by the ornamental trade. Dividing this by the number of invasive species (1,366) gives the average annual cost per invader ($2,068,100).

The ornamental plant industry in Australia had a total value in fiscal year 2003–2004 of $5.55 billion (36). This value includes all aspects of the industry, plants, gardening equipment, landscaping, and café/gift sales. Because nonindigenous plants account for 64.6% (37) of total plant sales, our estimate for the value of nonindigenous plants to the industry is $3.59 billion. We divide this value by the total number of species introduced (25, 360) to get the average annual value per species ($141,480). We use this value; the data needed to calculate a more accurate (lower) value per species do not exist.

Time Lags. The time between the introduction of a plant and its retail release ranges from 1 year (annual species) to 10 years or more (trees) (P. Bristol, personal communication). To account for the time between a species' introduction and the creation of economic benefits, we linearly incremented benefits from a cohort of introduced species over the 10 years subsequent to introduction. Hence, if a cohort of species is introduced in year t, the economic benefits in year $t + 1, t + 2, t + 3, \ldots, t + 10$ are 10%, 20%, 30%, . . . , and 100%, respectively, of the total eventual benefits from those species. After 10 years, the benefits from this cohort remain constant and are the product of the benefit per species and the number of species introduced in that cohort.

Lag times to invasion are generally poorly known. In our model, we linearly increment the costs of invasion from a cohort of introduced plants over the 50 years subsequent to its introduction in the same way that the benefits are time lagged. Although 50 years is at the low end of published lag times to invasion for plants (27, 38), we believe it is realistic for the ornamental trade, because species are specifically matched to their receiving environment and widely distributed geographically. Each of these factors would decrease the time it takes a plant to manifest invasiveness.

Projection. To project the two policy options (with and without RA), we have assumed that adoption of a policy implies it will be applied to the cohort of species proposed for introduction in each year. We have performed a sensitivity analysis over four different discount rate assumptions. First, we follow Weitzman (21) and use a discount rate of 4% for years 1–5, 3% for years 6–25, 2% for years 26–75, and 1% for years 76–500 (the limit of our projections). The other three discount rates applied are constant at 3%, 6%, and 9%. Net present value of applying RA was calculated for time horizons of 10, 25, 50, 100, and 500 years. Results for the latter horizon are presented in SI Fig. 5.

Although the budget allocated to RA for plants in Australia is not available, we estimated the total required full-time staff at four, based on an average RA taking 2 days to complete (39), and some extra duties. Assuming average pay scales and overhead, we have estimated the annual cost of administering RA to be $300,000. Because of the relatively high values of invaders and trade, this parameter has a negligible effect on the analysis.

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