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BIOLOGICAL POLLUTION PREVENTION STRATEGIES UNDER IGNORANCE: THE CASE OF INVASIVE SPECIES

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Invasive alien species (IAS)—species that establish and spread in ecosystems to that they are not native—are argued to be the second-most important cause of biodiversity loss worldwide (Holmes). Without natural predators, parasites, and/or pathogens to help control population growth, IAS frequently outcompete or prey on native species. They cause or spread diseases to cultivated plants, livestock and human populations. They often encroach on, damage or degrade assets (e.g., power plants, boats, piers, and reservoirs). The associated economic impacts can be significant (Perrings, Williamson, and Dalmazzone). For example, the zebra mussel alone is predicted to create $5 billion in damages over the next decade in the Great Lakes (Michigan Department of Environmental Quality).

Human activities—particularly those associated with trade and travel—are the most common cause of IAS invasions. IAS invasions are now more frequent than ever before, largely due to the expansion of world trade and travel over the past century (Heywood, Parker et al.). For instance, at least 145 species have invaded the Great Lakes since the 1830s, with one-third occurring during the past thirty years—likely in response to increased shipping in the St. Lawrence Seaway (Michigan Department of Environmental Quality).

Management of IAS includes several options: prevention of new species introductions, eradication following introduction, containment or control of IAS populations (e.g., IPM), or adaptation. Historically, efforts have focused on eradication and postinvasion control. Preventive measures, including quarantine restrictions, import licensing by reference to "black" or "white" lists, biosecurity shipping measures and so on are authorized by article XX of GATT and the Sanitary and Phytosanitary Agreement. However, comparatively little effort has been committed to such measures.

We focus on preinvasion controls, treating IAS as a form of "biological pollution." Unlike many conventional pollution problems, IAS problems are difficult to handle within a conventional risk-management framework. There are several reasons for this: (*a*) Species introductions may be an increasing function of trade linkages and trade volumes, but the likelihood of establishment, spread, and damage are thought to be extremely low (Williamson). (*b*) Biological invasions frequently involve novelty. Bioclimatic models have been developed to predict the probability of IAS invasions. But many scientists argue that such research is futile because a probability density function cannot be constructed for one-time events with no historical precedents (Williamson). Decisions must therefore be made under conditions of incomplete information about the set of possible invaders, the likelihood of their introduction, establishment and spread, and the potential economic damages if they do. At the same time, the cost of invasions can be extremely high. (*c*) Once a species has

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established and spread, then its introduction is to all intents and purposes irreversible. At the very least it involves hysteresis.

For all three reasons, decision models based on standard expected utility theory have limited value. One problem is the insensitivity of expected utility to low probability catastrophic risk (Chichilnisky). Indeed, there is evidence that people treat probabilities close to zero in a distinctive way. The probability of "very unlikely" outcomes tends to be either overestimated or set equal to zero. The deviation of the perceived from the actual risk in these cases generally depends on the value of the outcome. Moreover, this occurs even in well-functioning risk markets. In liability insurance markets, for example, it has long been observed that insurers demand a risk premium that makes the rates exceed the expected losses when dealing with highly unlikely but potentially large losses. At the same time, the insured are willing to pay less than predicted by expected utility calculations (Katzman, Farley). Given that many IAS problems exhibit both potentially catastrophic and irreversible consequences and involve low (but largely unknown) probabilities, there is clearly a management problem to be addressed.

In this article, we examine the IAS preinvasion control problem using both ignorance and risk-management models. We begin with the more familiar risk-management framework, which might be advocated in the special case of full information. Next, we proceed using an ignorance (or uncertainty) framework. We indicate the information required to develop such a model, and we illustrate that rational policy design is possible under ignorance. Finally, we make qualitative comparisons between the two approaches.

Controlling Biological Pollution under Full Information: Risk Management

Consider a potential "pathway" for species invasions, which we may call biological pollution. A pathway involves both a route and a carrier or vector. We denote each potential carrier as a firm. In many cases it will make more sense to focus on the originating firm (the exporter), rather than the carrier. The carrier is relevant where species are introduced as unintentional cargo, as is the case with the many aquatic species introduced through the discharge of ballast water. Each firm makes a variety of production and biosecurity choices affecting the likelihood of species introductions (e.g., in the case of commercial shipping, these include the time and effort involved with ballast water exchange, the number and location of stops, the time at sea, and the use of biocides, filtering, and heat). The ith firm's choices are denoted by the $(1 \times m)$ input vector x_i (with jth element x_{ij}). Biosecurity or biological pollution control costs are $c_i(x_i)$.

The biomass of species s $(s = 1, \ldots, S)$ introduced in the given habitat by firm i is denoted by e_{is}. A firm cannot control e_{is} with certainty. Introductions are random due to the influence of stochastic variables that are not directly under the firm's control (e.g., environmental drivers), although the probability of a particular level of biomass emissions is conditional on the firm's biosecurity choices. The probability that e_{is} is introduced, conditional on input choices and firm characteristics (b_i) is $p_{is}(e_{is} \mid x_i, b_i)$.

A species that is introduced may or may not establish and spread (invade), and cause ecological and economic damages. Conditions, including the control regime (which we take here as given), must be right for a successful invasion. We assume damages only occur from a successful invasion. Such an outcome occurs with some probability, conditional on the scale of the introduction and also location and habitat characteristics (e.g., predators and food sources), denoted by w. The probability that an introduction e_{is} leads to a successful invasion is denoted by $\Pr_s$ (survival $\mid e_{is}, w$), and is increasing in e_{is}. Accordingly, the probability that introductions of species s by firm i lead to an invasion is $q_{is}(x_i, b_i, w) = \sum_{e_{is}} \Pr_s(\text{survival} \mid e_{is}, w) p_{is}(e_{is} \mid x_i, b_i)$. This specification assumes that invasions arise via particular firms and that the probability of an invasion via one firm is independent of introductions by other firms. This may be a simplification for some cases in which the alien population depends on a large number of introductions to become established in the new habitat. But it is realistic for species that are fairly well suited to the new ecosystem and can establish with only small numbers (e.g., invasive pathogens).

Because a species is able to proliferate *in situ* once it has invaded, we assume a species can only invade once and that the marginal damages of further invasions of the same species are zero. This is in contrast to many pollution problems in which the current level of emissions matters. It is analogous to pollution problems in which the marginal damage cost of pollution falls to zero once the assimilative capacity of the environment has been exceeded. A species invasion is a Bernoulli event: an invasion either occurs or it does not occur. The probability of an invasion of species s via any one of n firms is

$$(1)\quad P_s(x_1,\ldots,x_n) = P_s(Z_s \geq 1) = 1 - P(Z_s = 0) = 1 - \prod_{i=1}^{n}(1 - q_{is}(x_i, b_i, w))$$

where Z_s represents the number of times that species s invades a given ecosystem. The probability P_s decreases in biosecurity measures that make introductions less likely and increases in biosecurity measures that make introductions more likely. The probability P_s also increases in the number of firms. As $n \to \infty$, invasion becomes a virtual certainty (i.e., $P_s \to 1$). This is because IAS control depends on the least effective provider. For instance, in the case of quarantine services, if one quarantine facility does not contain an invasive pathogen, the fact that all others may do so is irrelevant. The similarity to the problem of control of communicable diseases is obvious. The public good involved in the control of invasive species and infectious diseases alike is a "weakest-link" public good (Perrings et al.).

The (present value of) economic damages due to an invasion by the sth species are $D_s(\gamma_s, \Omega)$, where γ_s is a random variable reflecting uncertain damage costs, and Ω is the set of species that may be introduced. The management response to the invasion is taken as given here, although a more complete model would consider the trade-offs between prevention and mitigation efforts. The set Ω can be thought of as a description of the state of the world, which will change over time as the system evolves. The state of the world is an argument of D_s because damages might depend on the order of species invasions as well as interactions that may arise as new species invade over time.

At least some of the random factors influencing the probability of survival will also influence damages. For instance, stochastic environmental variables that affect the probability that an introduced species will establish and spread may also influence its impact on the ecological services provided by the host system. Denote the common (sub-) set of random variables influencing both survival and damages by θ_s, and define the probability of survival, conditional on the value of θ_s, by $P_s(x_1,\ldots,x_n \mid \theta_s)$. Defining E as the expectations operator over all stochastic variables, expected damages are given by

$$(2)\quad \mathrm{E}\{D(x_1,\ldots,x_n,\Omega)\} = \sum_{s=1}^{S}\mathrm{E}\{D_s P_s(x_1,\ldots,x_n \mid \theta_s)\}.$$

Ex Ante Economic Efficiency

Ex ante efficient biosecurity measures minimize the expected social cost of biological pollution and its control

$$(3)\quad \min_{x_{ij}\forall i,j} \sum_{i=1}^{n} c_i(x_i) + \mathrm{E}\{D(x_1,\ldots,x_n,\Omega)\}.$$

The problem has been constructed in a static context for simplicity and, hence, the state of the world remains constant over the (single-period) planning horizon. The necessary conditions for an interior solution can be written as

$$(4)\quad \frac{\partial c_i}{\partial x_{ij}} = -\mathrm{E}\left\{\frac{\partial D}{\partial x_{ij}}\right\} = -\sum_{s=1}^{S}\left[\mathrm{E}\{D_s\}\mathrm{E}\left\{\frac{\partial P_s}{\partial x_{ij}}\right\} + \mathrm{cov}\left\{D_s, \frac{\partial P_s}{\partial x_{ij}}\right\}\right] \quad \forall i, j.$$

Condition (4) states that the marginal cost of undertaking a particular action (the left-hand side (LHS)) optimally equals the marginal expected benefits (i.e., the reduction in damages) of the action (the right-hand side (RHS)). The marginal expected benefits include both mean (the first RHS term) and risk (the second RHS term) impacts. The risk impacts occur because the specific choices made by each firm have uncertain effects on the likelihood of adverse environmental outcomes (e.g., see Shortle and Dunn).

Condition (4) can be expanded to illustrate the effects of redundancy

$$(5)\quad \frac{\partial c_i}{\partial x_{ij}} = -\sum_{s=1}^{S}\mathrm{E}\left\{D_s\left(1 - P_s^{-i}\right)\frac{\partial q_{is}}{\partial x_{ij}}\right\} \quad \forall i, j$$

where $P_s^{-i} = 1 - \prod_{k\neq i}(1 - q_{ks}(\bullet \mid \theta_s))$ is the aggregate probability (conditional on θ_s) that species s will invade from any firm other than firm i. As $P_s^{-i} \to 0$ it becomes highly unlikely that species s will invade via one of the other firms. For $P_s^{-i} \in [0,1)$, the optimal degree of biosecurity actions by firm i depends on the (firm-specific) trade-off between firm i's marginal likelihood of an introduction and its marginal costs of biosecurity, as weighed by $(1 - P_s^{-i})$. The value of P_s^{-i} is endogenous and is affected by the optimal choices for firm i. For instance, if $q_{is} > 0$ is optimal then $P_s^{-i} = 0$ cannot be optimal. When $P_s^{-i} = 0$, all firms $k \neq i$ have incurred costs to reduce the probability of an invasion to zero, but P_s has not been reduced below the probability created by firm i (q_{is}). A reallocation of biosecurity efforts across firms would lower costs while not increasing P_s.

As $P_s^{-i} \to 1$, then species s is very likely to invade via one of the other firms. In this case the sth bracketed term on the RHS of condition (5) becomes quite small, vanishing when $P_s^{-i} = 1$. If $P_s^{-i} = 1$ $\forall s$, then firm i optimally does not invest in biosecurity; firm i optimally goes unregulated. Note that $P_s^{-i} \to 1$ as $n \to \infty$; a corner solution arises when there are many firms. It is optimal either for all firms to go unregulated so that $P_s^{-i} \to 1$, or for each firm to undertake extensive controls so that $q_{is} = 0$ $\forall k$, s and $P_s^{-i} \to 0$. The results with $P_s^{-i} \to 1$ are consistent with those of Simpson, Sedjo, and Reid, who argue that the value of habitat and species at the (current) margin is small because there is redundancy in genetic information. Conservation to preserve genetic information is of little value because many other species are still around. In the present case, abatement is of little value when n is large because chances are the species will invade anyway.

A Decision Framework under Ignorance

In most cases the risk of invasion is unknown. Even the use of subjective probabilities may be problematic due to the unfamiliarity of IAS invasions and incomplete knowledge of the state space. Accordingly, a risk-management approach like the one described above may be infeasible. This does not invalidate the general approach, but it does imply that decision makers may approach the evaluation of outcomes in a rather different way.

One option is to model uncertainty and ignorance explicitly. Katzner's development of the pioneering works of Shackle and Vickers illustrates how (see Kelsey and Quiggin, Hamouda and Rowley for surveys of other approaches). Denote Ω_i to be the set of alien species that could potentially invade an ecosystem via firm i. Unlike the model above, some elements of Ω_i remain unknown. Identifiable elements of Ω_i are contained in a subset of Ω_i, denoted Ψ_i. The collection of unknown outcomes is represented by the empty set, ϕ_i, with $\phi_i \subseteq \Omega_i$ and ϕ_i a member of Ψ_i. "Hence, it is recognized that the inconceivable may occur" (Katzner, p. 47). Each member of Ψ_i is a hypothesis, which can be thought of as an answer to the question, "Given the choices x_i, populations of which species will invade via firm i?" Hypothesis A_i is rival to hypothesis B_i if and only if $A_i \cap B_i = \phi_i$. Of course, ϕ_i is rival to every hypothesis in Ψ_i.

The perceived likelihood that a hypothesis will occur is measured by a potential surprise function, denoted $\sigma_i(A_i, x_i)$. This is a measure of disbelief, or the degree of surprise that individuals expect they would experience should A_i be realized in the future (given the choices x_i). For instance, this function might be developed based on expert opinion. When $\sigma_i(A_i, x_i) = 0$, then individuals are unable to imagine a barrier to the occurrence of A_i; event A_i is considered very likely or, rather, perfectly possible. When $\sigma_i(A_i, x_i) = 1$, individuals are unable to imagine A_i occurring; event A_i is considered very unlikely. Potential surprise functions are therefore closely related to inverse subjective probability density functions, although they do not have to sum to one over events.

Each species can invade only once, but it is useful to consider the potential surprise that may be engendered if an IAS invasion was to occur via any firm, denoted $\sigma(A, x)$, where x represents the vector of each firm's choices. If A_i represents the same (collection of) species for each i, then we have (Katzner, p. 51)

$$(6) \qquad \sigma(A, x) = \sigma(A_1 \cup A_2 \cup \ldots \cup A_n; x) = \min[\sigma_1(A_1, x_1), \sigma_2(A_2, x_2), \ldots, \sigma_2(A_n, x_n)].$$

Biosecurity measures taken by one firm do not increase the potential surprise of an invasion if all other firms do not also undertake preventative actions. As above, biosecurity measures are a weakest-link public good.

If an invasion does occur, then damages are also uncertain. The set Ω therefore represents just one of the incomplete sets of outcomes with which we are concerned. A second hypothesis set, denoted Λ, and associated potential surprise functions are needed to answer the question, "If species invasions do occur, then what will be the economic damages (again, taking the management response to the invasion as given)?" Here, conditionality is not modeled by assuming the event did occur (as in probability theory), but rather that the event is perfectly possible. The conditional potential surprise associated with a particular level of damages, denoted by an event z, given that event $A \subseteq \Omega$ is thought to be perfectly possible, is denoted $\rho(z \mid \sigma(A, x) = 0)$. But *ex ante*, it is not known whether the species will invade. The potential surprise associated with a particular level of damages therefore also depends on the potential surprise of an invasion. Following Shackle, the potential surprise associated with outcome z is

$$(7) \qquad \rho(z, x) = \min_A\{\max\{\rho(z \mid \sigma(A, x) = 0), \sigma(A, x)\}\}.$$

Hence, potential surprise is endogenous, to a point. The level of disbelief may increase as biosecurity measures are increased. But this only occurs to the extent that the disbelief associated with possible invasions is greater than the disbelief associated with damages when the introductions are considered perfectly possible.

The major insight of this approach to decision making is the following. While several possible outcomes z may be associated with each value of x, a decision maker will not focus on all possible outcomes. Instead, when evaluating x, a decision maker will focus on "the least unbelievable conjectured losses or gains from the activity" x (Perrings, p. 109). Focusing on losses in the present case, this means that, for a given x, the decision maker focuses exclusively on those pairs $(z, \rho(z, x))$ that maximize the attractiveness of losses—the focus loss, defined as $[z^-(x), \rho(z^-(x), x)]$ (see Katzner for derivations). Hence, when the decision maker evaluates x, his/her attention is drawn to only $z^-(x)$, which is the endpoint "of a closed interval of outcomes for x having 'minimal' potential surprise" (Katzner, p. 128).

To calculate the optimal choice of x, note that the focus loss components are functions of x. So all that is required to choose x optimally is knowledge of how the decision maker values the focus loss components. Just as expected damages are a decision index based on damage levels and their probabilities of occurrence, define Q to be a decision index based on the focus loss components (Vickers, Katzner), that is,

$$(8) \qquad Q(x) = Q(z^-(x), \rho(z^-(x), x)).$$

The index Q is an inverse measure of welfare and therefore increases in damages, that is, $\partial Q/\partial z^- > 0$. Assume the decision maker is uncertainty averse, placing a negative value on greater uncertainty associated with desirable outcomes. Alternatively, the decision maker values greater uncertainty associated with the focus loss, that is, $\partial Q/\partial\rho(z^-, x) < 0$. This is analogous to having convex damages in the risk-management case.

We now incorporate Q into the more general problem of minimizing the social costs of biological pollution and its control. Following Perrings, we combine traditional economic welfare measures with an appropriately defined decision index Q:

$$(9) \qquad \min_{x_{ij}\,\forall i,j} \sum_{i=1}^{n} c_i(x_i) + Q(x).$$

If Q is differentiable, then the necessary conditions for this problem are

$$(10) \qquad \frac{\partial c_i}{\partial x_{ij}} = -\left[\frac{\partial Q}{\partial z^-}\frac{\partial z^-}{\partial x_{ij}} + \frac{\partial Q}{\partial \rho^-}\frac{\partial \rho^-}{\partial x_{ij}}\right] \ \forall i, j.$$

Condition (10) indicates that a firm's marginal cost of using an input (the LHS) optimally equals the marginal impact of the input on the damage index (the RHS). Similar to condition (4) in the risk-management case, the RHS of (10) consists of two components. The first term is the marginal impact of the input on the focus loss (analogous to the mean impacts in the risk-management case). The second term is the marginal impact of the input on the potential surprise associated with the focus loss (analogous to the risk impacts in the risk-management case). This second term measures the uncertainty impacts from the use of the input: the marginal cost of an input should increase when the use of the input increases the uncertainty associated with the focus loss.

But as it turns out, Q may not be differentiable at the optimum. To see this, consider the allocation of uncertainty impacts across firms. Suppose that firm i adopts sufficient biosecurity measures that the surprise of an introduction by firm i is greater than the surprise of an introduction by at least one other firm k, that is,

$$(11) \qquad \sigma_i(A', x_i) > \sigma_k(A', x_k).$$

In this case, condition (6) implies that $\partial z^-/\partial x_{ij} = \partial\rho^-/\partial x_{ij} = 0$, which in combination with condition (10) means that $\partial c_i/\partial x_{ij} = 0\ \forall j$. That is, the firm should not adopt any biosecurity measures, which is in contrast to the assumption that firm i has adopted the most stringent pollution controls. Therefore, condition (11) cannot hold in the optimum condition. If biosecurity measures by one firm have no impact on the potential surprise of an invasion, it is not optimal for firm i to have a greater potential surprise of an introduction than any other firm. Instead, it is optimal for $\sigma_i(A', x_i) = \sigma_k(A', x_k)\ \forall i$,k. As a result, equation (6) may be kinked for small changes in any x_{ij}, and so Q may not be differentiable when $n > 1$. The solution to (9) still requires balancing costs with the decision index Q, although with the x_{ij}'s being chosen from the set $\Gamma = \{x_{ij} \mid \sigma_i(A', x_i) = \sigma_k(A', x_k)\ \forall i, k\}$.

Implications of Uncertainty for the Management of Invasion Risks

The critical point in the theory of decision making under uncertainty is that decision makers form impressions about the likelihood of future events in ways that are either nonprobabilistic or that modify the underlying probability distribution of future outcomes. Shackle suggested that under uncertainty the focus loss and focus gain of a decision attract the decision maker's attention, without necessarily representing any particular moment of an underlying probability distribution. The empirical evidence on decision making under incomplete information confirms that in the absence of full information people do weight probabilities both as a function of their confidence in the data and the value of the outcome. The form of the weighting function and even the existence of explicit weights are empirical matters. But all nonprocedural approaches to decision making under uncertainty can in fact be represented in this way. Subjective probability (Savage), insufficient reason (Arrow and Hurwicz), weighted expected utility (Fishburn), and potential surprise (Shackle) all assume that the focus of the decision maker's attention is something other than the expected utility of the outcome.

We examine how uncertainty may modify risk-management decisions (assuming the state space is known and subjective probabilities could be constructed) by mapping the focus of decision makers' attention into expected utility. Because Q is not differentiable for multiple firms, we consider the case of $n = 1$. There exists a probability weighting function that equates the uncertainty decision index $Q(z^-(x), \rho(z^-(x), x))$ with the expected damages of the same set of actions, $E\{D(x, \Omega)\}$. Specifically, there exists a weighting function $G_s(x, \Omega)$ such that the weighted probability function $\Pi_s(P_s, G_s)$ $(\partial \Pi_s / \partial G_s > 0, \partial \Pi_s / \partial P_s > 0)$ ensures that the following relation holds:

$$
(12) \qquad Q(z^-(x), \rho(z^-(x), x)) = \sum_{s=1}^{S} \mathrm{E}\{D_s \Pi_s(P_s, G_s)\}.
$$

As an example of how a weighting function might map focus loss into expected value, consider a rank-dependent transformation of the general form of that suggested by Lattimore, Baker, and Witte: $\Pi_s(G_s, P_s) = G_s P_s^{\beta} / [G_s P_s^{\beta} + \sum_{r=1, r \neq s}^{S} P_r^{\beta}]$. As above, G_s is an outcome-specific weight. If $\beta = 1$ and $G_s = 1\ \forall s$, then Π_s is identically equal to the unweighted expected value. If G_s is greater or less than unity, the weighted probability is greater or less than the unweighted probability. We would expect the outcomes that constitute the focus loss of an action (the reference point for the decision) to be weighted at greater than unity. All other outcomes would be weighted at less than unity. Note that the sum of the weighted probabilities need not equal one.

The parameter β has the effect of weighting small changes in the neighborhood of the reference point more (if $\beta < 1$) or less (if $\beta > 1$) heavily than large changes elsewhere. This captures a well-recognized empirical observation about people's perceptions of losses or gains relative to a reference point (Tversky and Kahneman). Starmer and Sugden, for example, suggest that the probability weighting function might be concave for gains and convex for losses around a reference point.

Using (12), the ignorance problem (9) can be written as a risk-management problem

$$
(13) \qquad \min_{x_j \forall j} c(x) + \sum_{s=1}^{S} \mathrm{E}\{D_s \Pi_s(P_s, G_s)\}
$$

with first-order necessary conditions

$$
(14) \qquad \frac{\partial c}{\partial x_j} = -\sum_{s=1}^{S} \left[\mathrm{E}\{D_s\} \mathrm{E}\left\{ \frac{\partial \Pi_s}{\partial G_s} \frac{\partial G_s}{\partial x_j} + \frac{\partial \Pi_s}{\partial P_s} \frac{\partial P_s}{\partial x_j} \right\} + \mathrm{cov}\left\{ D_s, \frac{\partial \Pi_s}{\partial x_{ij}} \right\} \right] \ \forall j.
$$

Because condition (12) holds, $\forall x$, the solution to (14) will be equivalent to that of (10). The results of the uncertainty model can then be compared with the risk-management model by comparing conditions (14) and (4). Relative to (4), the weighting function in (14) changes the expected marginal reduction in damages due to biosecurity measures. As in (4), the expected marginal reduction in damages in (14) includes both mean and risk impacts. Uncertainty increases (decreases) the mean and risk impacts as a function of the value of particular outcomes as $\partial G_s/\partial x_{ij} < (>)\ 0$. Therefore, when operating under uncertainty, it is optimal to devote more resources to confronting high-damage events that are considered possible (low potential surprise) even if the probability is low, and to allocate few or no resources to confronting events that are considered less possible (higher potential surprise)—regardless of the expected damages of those events. Similar results might be expected for multiple firms.

Finally, recall that $\partial P_s/\partial x_{ij} \to 0$ as $n \to \infty$, so that the RHS of (4) vanishes and no biosecurity measures are adopted. This may not be the case under ignorance as the effect of n on G_s is also relevant. Because G_s weights large damages having low potential surprise more heavily, a decision maker may be more willing to incur the larger abatement costs that might arise when regulating larger numbers of firms. This is somewhat speculative since it may not be possible to construct G_s for $n > 1$. Hence, numerical simulations might be useful to see how increases in n might affect the results.

Discussion

Under both risk and uncertainty, the optimal strategy for preventive measures to control IAS is to equate the marginal costs and benefits of biosecurity measures. However, the marginal benefits of biosecurity measures may be quite different where decisions are based on the focus loss rather than the expected value of an action. If there is no uncertainty, focus loss and expected value may be identical. If there is uncertainty, however, low-probability extreme outcomes that are considered possible (low potential surprise) will be "overweighted" relative to an expected value approach. They will attract more attention in the decision process, and more resources will be committed to avoiding them. This is consistent with a precautionary attitude to irreversible, low-probability events having high-cost consequences (catastrophes) to the extent that these events have low potential surprise. But if catastrophic events have a high potential surprise, then such events do not factor into the focus loss even if the potential damages are high.

For both the risk and uncertainty models, optimal prevention efforts are found by weighing the costs and benefits of control efforts. However, uncertainty changes the manner in which the marginal impacts by different firms are valued. As a result we find that the types of choices and associated policy implications arising under ignorance could be substantially different than those that would arise if the information on probabilities and state spaces were available. For instance, the risk-management model implies that the expected value of abatement might be small when there are many firms. A similar result does not necessarily emerge from the ignorance model due to the large weights attached to outcomes involving extensive losses. Significant abatement efforts might be recommended under the ignorance model even with many firms, while a risk-management structure might indicate the opposite extreme—that no abatement efforts are warranted.

Another policy implication stems from the result that the potential surprise values are optimally equated across firms (at least, in the weakest-link case modeled here), while the probability of an introduction is optimally firm-specific in the risk-management model. This difference affects policy choices, particularly to the extent that policies are based on some measure of performance. The ideal performance measure is emissions. However, in the present case it is not possible to monitor emissions or to control them with certainty. An alternative measure of performance is the likelihood of a species invasion, either the probability of invasion or potential surprise, depending on the decision framework. Under risk management, such performance-based incentives or limits would optimally be firm specific, complicating the administration of such programs. Under uncertainty, such performance-based limits (but not incentives) could be set uniformly across firms. Moreover, because of the discontinuities involved, a limit may appear more desirable because it does not give firms the flexibility to adjust their biosecurity choices. Under an incentive system one firm could reduce its potential surprise of an invasion relative to the other firms if this became a profitable endeavor. Such a move would decrease the overall potential surprise of an invasion since this depends on the minimum potential surprise value across firms. This would adversely affect the decision criterion Q. Moreover, at the new level of overall potential surprise, all other firms over-invest in biosecurity; their extra efforts have no impact on overall performance. Thus, management under ignorance may support current policy initiatives that are based mainly on uniform technology mandates as a way of limiting uncertainty uniformly across firms.

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