BIOLOGICAL INVASIONS: ASSESSMENT AND MANAGEMENT OF ENVIRONMENTAL RISK

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ABSTRACT

This Bulletin discuses the impact of exotic species on the ecosystem and the use of risk analysis to quantify the level of potential damage from each species. It outlines some of the ecological principles which can be followed in risk analysis, and how these can be used for intentional and accidental introductions, respectively. Finally, it discusses current international regulations and authorities which are attempting to minimize the risk of invasions by harmful exotic species in an era of global free trade.

INTRODUCTION

Invasions of exotic species can transform the ecosystem, exterminate native species, reduce global biological diversity, threaten human health, and harm many human activities. The total cost may be enormous. One study of the economic costs to the United States of a sample of exotic species estimates US$137 billion per year (Pimentel *et al.* 2000). Another study of the costs to the United States of various exotic human, plant and animal diseases estimates US$41 billion per year (Daszak *et al.* 2000). Worldwide, the costs of exotic species invasions must exceed hundreds of billions of dollars annually.

Ecosystems can be completely transformed by exotic species. Exotic species can disturb the hydrological cycle, nutrient cycling, conservation and regeneration of soils, and the entire biological community. In and near the South African Cape Floral Kingdom, a national park in South Africa, invasive trees have reduced water supplies for nearby communities, increased fire hazards, and eliminated some native species. Government expenditure for the manual and chemical control of these exotic species exceeds $40 million per year. It is estimated that the cost of restoring this ecosystem may reach US$2 billion (Turpie and Heydenrych 2000). Salt cedar (*Tamarix* spp.) dominates riparian habitats in the western United States (Zavaleta 2000). Because this species supports so few insects, leaf-eating, migrating insectivorous birds are being adversely affected.

Several important diseases have spread as exotic species. Bubonic plague spread from central Asia through North Africa, Europe, and China, using an exotic flea vector on an exotic species of rat. Rinderpest was introduced into Africa via infected cattle, and spread through domestic and wild herds of bovids in the African savanna. This resulted in a shift in the composition of mammals in the continent and may have caused the death of 25% of the pastoral peoples during the early 20th century. Presently, West Nile Virus is spreading in the United States, causing a declines in corvid populations of corvids (eg. crows, jays and magpies) and increasing the incidence of human encephalitis.

Exotic species have had a major adverse effect on many human activities. The spread of SARS caused tourism to collapse in many parts of east Asia during the peak tourist season of 2003. The weeds St. John’s wort and leafy spurge have degraded pastures all over the world. Rabbits have degraded grasslands in Australia (White and Newton-

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Cross 2000). Varroa mites have killed European honey bees in nearly every country (Wittenberg and Cock 2001). Zebra mussels and water hyacinth clog waterways. Tilapia introduced into Lake Nicaragua in Central America have destroyed native fish populations. They have now spread to the coastal zone, adversely affecting marine fisheries and estuarine nursery grounds (McKaye *et al.* 1995).

Every ecosystem in the world has been adversely affected by exotic species, and with the increase in international trade and movement of people, even larger adverse effects are expected in the future. We need to act to avoid or reduce these effects in the future. In this Bulletin, I shall discuss the development and status of risk analysis to avoid or reduce future adverse effects from exotic species.

RISK ANALYSIS

Environmental risk analysis is used to reduce the adverse effects on the environment. Risk analysis is often divided into two components, risk assessment and risk management (NRC 1983).

Risk assessment

Risk assessment is the process by which risk is measured. This measurement can be quantitative or qualitative, probabilistic or deterministic. In risk management, society determines how to address the risk, for example, whether to tolerate, mitigate or avoid the risk. Foot and mouth disease is considered a large risk to livestock production in the United States, and is managed by quarantine regulations (Enserink 2001). Similarly, it was a serious disease in the United Kingdom when an outbreak occurred in 2001. It was managed by the massive slaughter of diseased animals and those suspected of contacting the disease (Ferguson *et al.* 2001, Keeling *et al.* 2001). In the United States, foot and mouth disease is managed by avoiding risk, while in the United Kingdom, it was managed by mitigating the risk.

Risk assessment is frequently considered to have several stages: risk identification, hazard assessment, exposure assessment and a process to combine all of these. The identification of risks includes the identification of the potential adverse impact on the environment, the potential adverse consequences of these impacts, and the identification of who, or what part of human society, suffers the consequences of the risks. Hazard assessment is a ranking or quantification of the adverse effects and adverse consequences. Exposure assessment is a ranking or quantification of the likelihood that an adverse effect or an adverse consequence will occur. The final stage of combining these involves a critical process of giving a value to the risk.

In risk assessment, the valuation of risk is framed in terms of human values. The idea that biological diversity has an intrinsic value has not been incorporated into any environmental risk assessment process so far. In some risk assessment models (NRC 1996, Fig. 1), the valuation problem permeates the processes of risk identification and hazard and

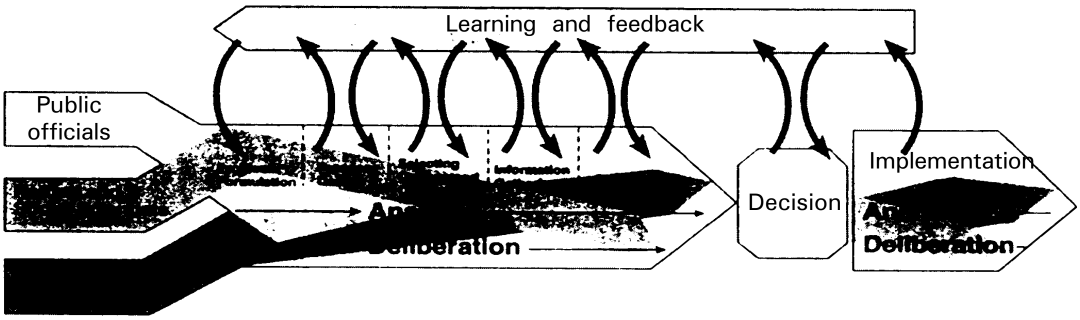

Fig. 1. Risk analysis model developed by NRC (1996), showing the focus of the process on decision making. Risk characterization is a synthetic process integrating analysis and deliberation

exposure assessment. In these cases, the entire process is called risk characterization. Characterizing environmental risks of biological invasions and introductions is still in a rudimentary state. This is primarily because the decisions are not clearly formulated, decision options are poorly characterized, the risks are not concretely identified, and ecological science is not focused on informing the decision making process.

Risk management

Risk management includes all of the processes aimed to influence the avoidance of risk, the perception of risk, the acceptability of risk, or the mitigation of risk. Management includes regulatory approaches that restrict, exclude or prohibit some exotic species, and actions that reduce risk, either by limiting exposure or limiting the harm to the environment. In this formulation, risk communication is a part of risk management, because risk communication influences how people perceive risks.

The development of a scientifically sound risk analysis for exotic species is difficult. Risk assessment is an imperfect activity. Any risk assessment procedure will eventually make a faulty assessment and some invasions will occur despite the best of intentions. Careful analysis of these new invasions should reveal the flaws in the past assessments and lead to improvements. Risk management procedures may also be flawed. Even when risks are assessed accurately, the risk management procedures may not be sufficiently effective to merit use, or the knowledge base may be lacking so that their use may result in additional risks.

Even if appropriate risk management procedures exist, they might not be implemented because of operational difficulties and/or economic constraints. These operational difficulties include a lax regulations, and organizational structures that inhibit proper response. Moreover, because risk analysis (both assessment and management) is a social activity, the cost of the analysis must not be excessive, and should probably not exceed its perceived benefits. In other words, even though invasions can be extraordinarily costly, a society may choose to under-invest in risk analysis because the benefits are perceived as insufficient.

Finally, the risk analysis must prove capable of reducing the costs associated with biological invasions. Such proof is difficult to provide. It is difficult to demonstrate that a preemptive action to reduce the risks of invasions has prevented the invasion from occurring. These considerations suggest the inherently contradictory position that a scientifically justifiable risk analysis process must use historical information about its failures to justify its effectiveness. Improvements can then be made, and the model retested or the assessment redone.

Some terminology

There are many difficulties associated with some of the terms used in discussing issues related to species invasions world-wide. Some of these difficulties arise from the variety of cultural meanings that the words take on when they are translated. There are also a number of different scientific frameworks that have been used to discuss these issues, and they use these terms in slightly different ways.

Exotic versus native

In this Bulletin, I shall use the term “exotic species” to refer to a species that is invading or has invaded, and “native species” to refer to one that is within its natural range. Although some authors prefer “alien”, I have a slight preference for “exotic”, because “alien” is often applied to foreign people.

Stages of invasion

The process of an invasion involves three stages: colonization, establishment and spread. Colonization must come before establishment, which in turn must come before spread. The processes involved in colonization are called “introductions”. The processes involved in establishment are central to population biology. Spread arises naturally from the growth of a population and the dispersal of its members, as long as there is some nearby suitable and unoccupied habitat.

Scale of environmental effect

Most exotic species have little detectable effect on the environment (Williamson 1996). Those species that do have a measurable effect on the environment are called invasive species. Invasive species may have a large or small effect on the environment. These effects may be local, or extend across large geographic areas. Invasive species that have large effects over large geographic areas are called transformer species. These are the exotic species we most wish to avoid, because they have the capacity to destroy native habitats by transforming them into new communities and ecosystems.

IDENTIFICATION OF ENVIRONMENTAL RISKS

The environmental risks of biological invasions have not been completely identified. This remains a complex problem. Early in the 1900s, the most widely recognized category of risk was the risk of plant pest, that the invading introduced organism would cause some plant to grow less vigorously. Many national quarantine acts were established because some exotic plant pest harmed an important plant. Although plant-pest risk remains one of the key environmental risks of exotic organisms, many other categories of detrimental environmental effects have been established, such as the modification of ecosystems processes, the whole transformation of ecosystems, and the loss of native species.

The challenge in identifying these other environmental risks is that while the category is readily understood, it includes many kinds of concrete risks. For example, for the loss of native species is easily understood as an environmental risk. However, to assess this risk it becomes clear that there actually many specific risks, and that “loss of native species” is a large complex category of risks.

Specifically, there are at least two important complications. First, there are many biological mechanisms that result in the loss of native species, so the association between an exotic species and the loss of a native species requires multiple kinds of assessments. This means that it is difficult to map the actual risks to a particular exotic species in anything but a crudely descriptive, non-predictive way. Second, these risks are in part a function of social values. Not all species are treated as equal in terms of their need for preservation. In the United States, a nematode is not valued as highly as the American bald eagle or the Monarch butterfly.

Two considerations that are often overlooked in the risk identification process are fairness and rights (NRC 1996). Which groups of people which organisms or which ecosystems are exposed to the greatest risks? In addressing the issue of fairness, it may become necessary to consider the total risks of these exposed groups rather than only the incremental risk of exotic species. For example, a group of poor people in South Africa may depend on the quality of certain waterways for their livelihood. While the additional risk associated with an exotic species may be small for these people, its absolute effect may be devastating compared to that experienced by wealthy people. At present there is no scientific research that has identified the effects of exotic species on different human groups. In contrast, considerable research has been conducted to show that some habitats are at greater risk than others. For example, small oceanic islands are at particular risk from exotic species (Simberloff 1986).

FRAMING ENVIRONMENTAL RISK ASSESSMENT

Most biological invasions are either intentional or accidental introductions. Intentional introductions should be distinguished from accidental (= unintentional) introductions, because they will have different risk assessment and management. Intentional introductions begin with a known exotic species, so the risk assessment can be species specific. Accidental introductions cannot be species specific, because the exotic species is not known prior to the accident. Intentional introductions can be managed by restricting or regulating the introduction. Accidental introductions can be managed only indirectly, by reducing the likelihood of establishment.

Intentional introductions of exotic species have been extremely damaging to the environment. Intentional introductions include horticultural plants (Japanese knotweed into Europe; purple loosestrife into North America), crop plants (bird’s foot trefoil into North America), other potentially usefully plants (kudzu into North America; Monterey pine throughout the world), vertebrate pets (mice, birds, frogs, fish, etc.), potentially useful vertebrates (muskrat into Europe; mongoose into many oceanic islands), potentially useful invertebrates (gypsy moth into North America; Africanized honey bee into South America; apple snail into east Asia). Indeed, if we consider exotic plants and animals, intentional introductions have been more damaging than accidental ones (Mack 1991; Mack and Lonsdale 2001; Reichard and White 2001; Ruiz and Carlton 2003).

Accidental introductions may occur in association with other products. We have no good idea how many exotic species may enter with these products, because only a minute percentage of imported goods are actually inspected for the presence of exotic species. Typically we become aware of these species only after they have established. These species can arrive associated with dry ballast (such as soil, the likely source of many beetle introductions), water ballast (the source of many aquatic exotics, such as Zebra mussel into the Great Lakes of North America), packing materials (the likely source of Asian longhorned beetle into North America), and plant pests associated with their host plants (cassava mites into Africa, soybean aphid into North America).

What can be done to prevent or avoid risks from exotic species? The simple answer to this question is to stop the movement and introduction of exotic species. Although this may be possible in theory, in practice it is not. It is not possible to prove that any human action will cause no environmental harm (impossible to prove a negative), so stopping movement and introduction cannot be sustained scientifically. More significantly, it is not possible to halt international commerce for the sake of preventing damage from exotic species. Consequently, risk assessment is needed.

Use of ecological principles in risk assessment

Intentional releases

There has been a great deal of recent research to uncover ecological patterns in exotic species invasions. What are the characteristics that enable some species to have a high probability of colonizing, establishing breeding populations, expanding their geographic range, and/or having an adverse effect on the environment? What are the characteristics of the invaded habitat that make it susceptible to invasion by these species?

The answers to these questions depends on which species and which regions of the world are under consideration, but some general factors have emerged (Mooney and Drake 1986, Kornberg and Williamson 1986, Groves and Burdeon 1986, Drake *et al.* 1989, Di Castri *et al.* 1990, Groves and di Castri 1991, Ramakrishnan 1991, Yano *et al*. 1999, Kolar and Lodge 2001). A species with a large natural range, with a high intrinsic rate of population growth, and which arrives in the new habitat with a large founding population is more likely to invade. Habitats where few species are present, and which have a high degree of habitat disturbance and an absence of species similar to the invaders are more likely to be invaded. Such generalized invasion patterns, however, all have a statistical basis. This limits their usefulness for prediction about particular cases. This lack of predictive power has limited their value for risk assessment.

As additional data are analyzed, these broad ecological generalizations will probably be modified and become more-specific (Kolar and Lodge 2001). Specific analyses may become useful for risk analysis of intentional releases, because they may have greater predictive power. For example, Rejmánek and Richardson (1996) proposed a set of ecological characteristics that accurately ranks historical invasiveness patterns in pines (*Pinus* spp.). If verified, this kind of information might lend scientific support for the development of lists of prohibited (or allowable) exotic species. For example, exotic species with a history of invasiveness could be compiled into a list of prohibited species.

Accidental releases

Another reason why these questions have not been useful for risk analysis is because we cannot use the answers. It is difficult or impossible to reduce the risks by changing the characteristics of a species, or managing a habitat. For example, how can we alter the intrinsic reproductive potential of a species. Suppose we knew the intrinsic reproductive potential for all possible exotic species. Putting aside for the moment, the relatively low predictive power of this ranking, it is not clear how this information by itself could be used to improve risk management. How can we intercept species with a high reproductive potential efficiently? How would the information help eradicate such species if they became established? How would the information help mitigate any adverse environmental effects from such a species?

There are several ecological patterns that may be useful for risk analysis associated with accidental releases.

The "Tens" rule

Williamson's (1996) ten's rule has important implications for risk analysis. The ten's rule suggests that the majority of potential invaders will either not become established, or will or not cause ecological damage. It suggests that only around 10% of the species that arrive will become established. Of those that become established, only about 10% will have an ecological impact. Although the quantitative values are still disputed (e.g., Smith *et al*. 1999), the rule implies that the process of risk analysis must efficiently distinguish between the many inconsequential exotics and the relatively few harmful ones.

Trade

The establishment of exotic especies has a positive correlation with the volume of international trade (Sailer 1978, OTA 1993; Mills *et al*. 1994, Kiritani and Yamamura 2003). The increasing volume of trade has increased the opportunity for accidental introductions. Changing modes of trade have also provided new groups of organisms with the opportunity to invade. For example, the development of rapid trans-Atlantic steam shipping during the late 19th century made possible the shipping of having plant material, which led to the introduction of many scale insects (Sailer 1978). This implies that trade should be examined to reduce the risks of alien introductions. This must be a rapid, efficient process to focus examination on the relatively few risky trade vectors. It should cover the mode of transport, the habitat of origin and the receiving habitat. Given our earlier experience, any significant changes in the mode of transport should be examined for their potential for the accidental introduction of new alien species.

History

Another important pattern is that species that have been invasive in one place are more likely to be invasive in other places (Williamson 1996). This historical information provides a powerful sieve for isolating relatively harmful species. Research to identify invasive species worldwide will help in the development of decision-making processes to characterize and manage these risks.

Changes in the original habitat

The potential of a species to invade can change because of changes in its habitat of origin or evolutionary changes in the species itself. For example, the recent invasion to the United States by the Asian long-horned beetle, *Anoplophora glabripennis* (Motschulsky) may be related to the substantial increase in plantings of hybrid poplar in northern China, a favored host plant of the beetle (EPPO 2001). This increase in planting area caused a substantial increase in beetle populations, which increased the probability that exports from northern China would carry the beetle. Many other invasions may be related to the population growth of the potential invader in its habitat of origin.

Evolution of the exotic species

Species also evolve in terms of moving into new habitats, and may become potentially invasive as a consequence. For example, the rice water weevil (*Lissopterus oryzae*) is found on wetland grasses in its native range on several Caribbean Islands (Iwata 1979). It invaded the southern United States early in the 20th century, but was restricted to native wetland grasses. In Louisiana, a major producer of rice, it evolved the ability to feed on rice. Somewhat later a parthenogenic strain (i.e. a strain which could reproduce without mating) evolved from that rice-feeding strain. Around 1959, the parthenogenic strain invaded California rice farms, and in 1976 it was detected in Japan. It subsequently invaded mainland Asia. Thus, the invasion of rice water weevil into Asian rice paddies occurred because of evolution in both the host range and the reproductive strategy of the beetle.

Similarly, Colorado potato beetle became invasive only after its host range evolved to include potatoes (Hsiao and Fraendel 1968). Although it is possible to predict that such evolutionary changes can create additional exotic species problems, it is impossible to predict which species will be involved.

Changes in the recipient habitat

The habitat being invaded can also change in ways that enable more species to invade it. For example, the crop or other suitable habitat in an area could increase, thereby increasing the probability of establishment. There is a positive, correlation over time between the area of greenhouse production in Japan and the history of invasions of greenhouse pests (Fig. 2). Large numbers of insect invasions did not occur until greenhouse production had increased sufficiently. In addition, these data suggest that the probability of invasion may have increased as the area of greenhouses increased. However, as Kiritani (1999) noted, greenhouse fauna is now homogeneous all over the world. This indicates that the invasion rate into Japanese greenhouses should now be declining.

Changes in the dispersal pathway

The dispersal pathway may change to influence the likelihood of invasion. Sailer (1978) showed that changes in types of invaders into the United States were correlated with changes in shipping practices. Exotic beetles (Coleoptera) associated with soil ballast in ships arrived when the use of soil ballast predominated. Exotic plant-dwelling Homoptera became dominant when it became economic to ship live plant materials. Aquatic invasions into the Baltic Sea occurred as a result of the building of canals in Eastern Europe. These provided a continuous aquatic pathway from the Black and Caspian Seas to the Baltic Sea

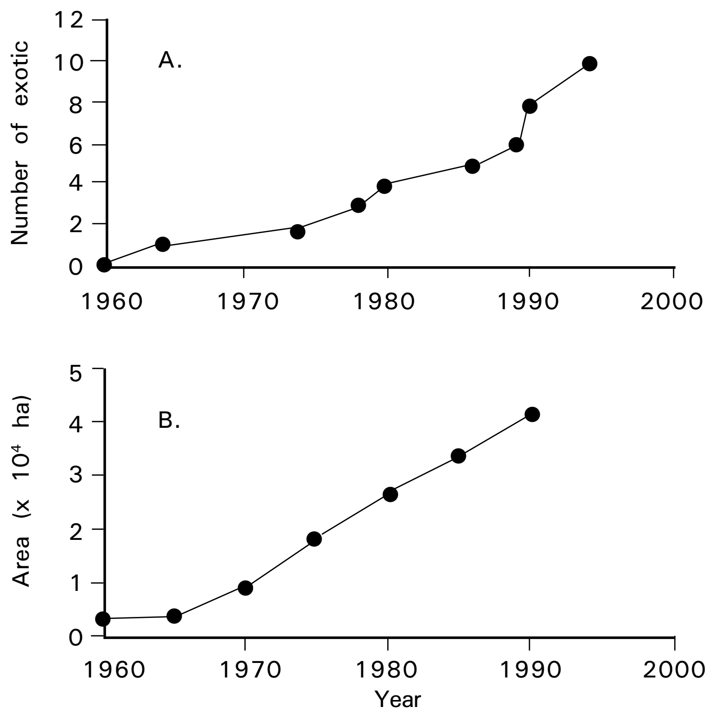

Fig. 2. Insect invasions into greenhouses in Japan. A) Cumulative number of exotic insect species establishing in greenhouses in Japan. Data are cross-referenced between Morimoto and Kiritani (1995) and Kiritani (1999). B) Area of crops produced under greenhouses in Japan. Data are from crop production records published by the Ministry of Agriculture, Forestry and Fisheries in Japan

(Ruiz and Carlton 2003). Similarly, the dramatic increase in containerized shipping has altered invasion risk significantly (OTA 1993, p. 80). In containerized shipping, goods are loaded into a container at the factory or other point of origin. The entire container is sealed and taken to the port, loaded aboard the ship, shipped and unloaded intact, and then transported to the point of use (recipient factory, warehouse etc.), where the container is opened. Through the use of containers, potential invaders can enter the container far from the port of origin, and can be delivered to suitable habitats far removed from the destination port (OTA 1993).

RISK ASSESSMENT FOR INTENTIONAL INTRODUCTIONS

In general, it is not yet possible to use ecological principles to predict the environmental risks of particular exotic species. Many ecologists suggest that further research is needed. In a certain sense this is correct, but it may not be necessary. Usually ecologists frame the prediction problem as follows: given any particular species and an identified risk (probability of establishment, probability of adverse environmental effect, etc.), use ecological data to predict the ecological risk associated with that species. The taxon-specific analyses mentioned above represent one line of investigation to improve predictive power. The risk assessment framework used to evaluate introductions of weed biological control agents is another model that can be considered more generally for intentional introductions of exotic species.

Excellent prediction may not be necessary for effective risk assessment and management. Instead, a scientific approach which reduces uncertainty may be crucial for developing effective and efficient risk analysis (Smith *et al.* 1999). The problem might be how to develop procedures that sort exotic species into successively smaller groups of species with increasingly higher risks and increasing potential for significant environmental harm. One sieve might be history. Any species that has caused significant environmental harm somewhere in the world might be restricted from introduction unless it could be shown to be safe. Additional sieves need to be developed. Of the established alien species that have caused no discernable ecological harm in their new habitat, what factors can predict the species that could cause ecological harm in a different invaded habitat? Of the alien species that have not become established anywhere beyond their native range, what factors can predict the species that could cause ecological harm in another invaded habitat? Neither of these problems has been addressed in the ecological literature, but answers might contribute to improvements in risk assessment for intentional introductions. For exotic pests, the problems can be restated as: Given that the species is an established exotic non-pest somewhere else, under what conditions is it likely to become a pest here? Given that the species is a native pest but not yet an exotic pest, is it likely to become a pest here? Clearly, considerable ecological research could be conducted to improve the risk assessment for intentional introductions of exotics species.

RISK ASSESSMENT FOR ACCIDENTAL INTRODUCTIONS

Can our ecological principles be used to improve risk assessment for accidental introductions? The analysis of Smith *et al.* (1999) can be used to provide a complex answer to this question. It suggests the utility of an ecological principle which depends on:

- The rate at which potential invaders become successful invaders (they call this the base rate);
- The accuracy of the principle in predicting the outcome for any particular species; *and*,
- The cost of allowing a damaging invader to occur, relative to the cost of excluding a potentially useful organism.
- If the base rate is 2% (i.e., 2% of the potential invaders actually establish), and the relative cost is 8 (i.e., the damage caused by the successful invader is 8 times the cost of the interception and quarantine system), then the ecological generalization must be at least 85% accurate to merit using it to modify an existing evaluation system. If the generalization were less accurate, it would be more cost effective simply to ignore it and not change the evaluation system.
- To my knowledge, none of the present

ecological generalizations approaches this level of accuracy. Hence ecological principles may be useful only when the base rate is greater than 2% and/or the relative cost is more than 8. These conditions can be met by focusing risk assessment on situations that are most likely allow exotic species to become established and/or situations that are particularly damaging in relation to the cost of keeping them from happening. Recent developments in risk assessment seem to be headed in this direction.

Pathways of accidental invasion

Risk assessment of accidental species invasions has been improved greatly thanks to the analytic framework initiated by Whiteaker and Doren (1989) and developed by Orr *et al.* (1993). The United States Department of Agriculture has used this framework to conduct risk assessments associated with several commodities. The model is a pathway-centered analysis, focused on a particular important commodity that also serves as a dispersal pathway for exotic species. The protocol involves listing all the known exotic species that could become associated with the commodity in the habitat of origin. Each species is then ranked, in terms of the probability of establishment and the probability of harmful economic or environmental effects. From these two qualitative measures, a single estimate of unmitigated invasion risk is calculated for each species. Risk management activities are then evaluated according to how much they can mitigate invasion risk.

For example, the risk of importing pests hidden in raw pine and spruce logs from Mexico into the United States has been evaluated using an expert panel to assign qualitative risk measures (Thacz *et al.* 1998). They compiled lists of potential pests associated with Mexican species of pine and spruce. Of these, they chose 22 pine and 6 spruce pest species for additional analysis, since they considered that these species were representative of three ecological niches associated with raw logs. They expected that risk mitigation measures aimed at the selected species would also mitigate risks associated with other species inhabiting a similar niche. Eight species were rated with a high risk potential, either for their potential economic effects (tree mortality, wood damage), or their probability of establishment. They concluded that import regulations should address pest importation from Mexico, that the present general permit for unprocessed wood from Mexico should be reassessed, and that the United States Department of Agriculture should review methods to mitigate these risks.

The value of this framework is that, by focusing on the dispersal pathway, the scope of the risk assessment is narrowed. Another benefit is that the outcome can be integrate directly with risk management activities. In contrast, an analyst using a species-based or habitat-based assessment procedure would have to consider many different potential invasion events, some of which might be difficult to anticipate. If we focus on a single dispersal pathway, the main source of uncertainty is identifying which species might invade using that pathway. Moreover, unlike species characteristics, which are impossible to manage, and habitat characteristics, which society is reluctant to manage prior to an actual invasion, it is possible to manage dispersal pathways. This can be done either by altering their flow or by monitoring their content.

Pathways based risk assessment

Australia has aggressively implemented pathways based risk assessment for exotic species. As a part of this effort, Stanaway *et al.* (2001) evaluated the risk that sea cargo containers might introduce insect pests. About 25 years ago, Australia required that all such containers, which were made of wood, should either be registered as permanently treated against potential pests, or be inspected every time the container landed in Australia. Containers are now made of steel with plywood floors. Australia requires that all containers are treated, but no longer registers them. Verification is carried out by random inspection and analysis of the wood components.

Only one of 3001 containers had insect damage to the wooden floor, suggesting that the containers were not a major risk. Timber pests, however, were detected in 3.5% of the containers, implying that timber dunnage (low grade timber used for packing and stabilizing goods) is a risk pathway (Ciesla 1993). About

0.5% of the containers had aggressive agricultural or nuisance pests that probably collected in containers, while 10% had postharvest pests that were transported in grain inside the containers. Thus, the wood from which the containers were made was not an important dispersal pathway for timber pests, but wood inside the containers could be an important one. Moreover, the containers could be an important pathway for pests that found shelter in the container, or for pests associated with the contents of the containers. Stanaway *et al.*'s (2001) findings provide clear guidance for quarantine and other risk management activities.

This pathways-centered risk assessment means that we should assess again many scientific issues and questions. For example, new ecological analyses may be important, including:

- How are different pathways distinguished from each other?
- What kinds of species are associated with particular pathways?
- To what kinds of habitats do the pathways deliver potential invaders?
- What pathways result in the greatest risks of invasiveness?

Research on these questions could help improve the scientific basis for risk assessment of exotic species, and focus attention on particularly risky species.

A pathways based risk assessment can be responsive to changing conditions for invasion. We can monitor changes in the probability of invasion by looking at factors that might affect these probabilities. Invasion probabilities are a product of three probabilities:

- The probability that a species will leave its habitat of origin;
- The probability that it will be transported to a new habitat, *and*,
- The probability that it will be able to establish in the new habitat.

The first may be related to the area occupied by the species in its habitat of origin. Hence, fluctuations in this might be monitored by measuring land use changes in the habitat(s) of origin. The second might be proportional to the volume of material that is shipped between two locations, so the probability might fluctuate with changes in shipping volume. The third might reflect how much suitable habitat is available for the organism in the new environment, so monitoring land use in areas vulnerable to invasion may detect fluctuations in the probability of establishment. In addition, it might be possible to construct a pathways approach to assess risk for two scenarios, one of with a large shipping volume, and the other of a small shipping volume. A large shipping volume should be more carefully monitored, because, all things being equal, the invasion risk is higher through dominant pathways.

Changes associated with a large-volume pathway, such as a major trade route, could enable a new invasions to occur. If practices change, such as the use of shipping containers, then it is possible that a different set of species from the originating habitat will become associated with shipments and new invasions will occur. Hence, risk assessment covering the whole process of shipment, from beginning to end, could be triggered if a change in shipping practice occurs at some portion of the shipping route. In addition, major changes in the landscape or land use patterns, either in the country of origin or the receiving country, could trigger additional risk assessment. For example, as the dominance of greenhouse production increased in Japan from the early 1960's (Kiritani 1999), additional regulatory oversight could have been triggered in Japan to guard against the establishment of many greenhouse pests. Even if this had only delayed establishment of some pests by a few years, the benefits might have been substantial. An increase in the volume of previously small-volume pathways, such as minor trade routes, could also increase the risk of invasions. For example, the shipping route from northern China to the US has much larger volume today than it had 20 years ago. The increase might have triggered monitoring to assess whether it would change the invasion risks. If this had been done, it might have been possible to recognize the risks associated with the wood shipped from this region, and perhaps the establishment of Asian long-horned beetle could have been avoided or at least delayed.

These examples illustrate that a pathways-based risk assessment model can adapt to changing patterns of invasion risk. The scientific basis for relating changes in pathways to changes in invasion risk needs to be developed, but these examples argue that an adaptive risk assessment model is needed.

LEGISLATING AUTHORITY FOR RISK ANALYSIS

Risk analysis is authorized through various country-specific plant pest and quarantine laws and several international agreements. Most of the international agreements aim to harmonize procedures so that there are no significant differences between countries. I shall compare two international agreements and the specific risk analysis models that they specify, focusing on the World Trade Organization (WTO) and the Convention on Biological Diversity (CBC).

The SPS agreement

On 15 April 1994, the Final Act of the Uruguay Round of Multilateral Trade Negotiations was signed, authorizing the Agreement on the Applications of Sanitary and Phytosanitary Measures (the SPS Agreement of the WTO). This agreement allows members to restrict international trade to protect human, animal or plant life or health from pests and diseases, as long as the restriction is necessary and scientifically justified. These restrictions are called “sanitary or phytosanitary measures.” They apply to all plants and animals within the territory of member states. Clearly, these measures could be used to protect against the adverse effects of invasive species, because all such effects directly or indirectly harm animal or plant life or health. Because restrictions can be applied only when they are necessary and scientifically justified, the SPS Agreement makes a presumption of safety and places the burden of proof on demonstrating risk. In addition, because the Agreement is a trade agreement, members must employ measures that minimize trade restrictions while achieving an acceptable level of protection. This means that when sufficient scientific information exists, the sanitary or phytosanitary measures can restrict trade, but methods that have the smallest effect on trade must be used.

Under conditions of uncertainty, members may restrict trade (Article 5, paragraph 7), but this is a provisional decision and they are obligated to obtain the scientific information to justify their actions in a reasonable period of time. The time frame is not specified in the Agreement, and the possibility that a country may not have the capacity to obtain the information is not discussed. These ambiguities could result in increased risk of species invasions. However, the interpretation of this clause will probably occur through case decisions, and has not yet been completely settled.

One of the key provisions of the Agreement is to designate certain international standards, guidelines and recommendations as being necessary to protect human, animal or plant life or health. The Agreement identifies three of them, and provides a means to add additional ones. For food safety, the Agreement identifies the Codex Alimentarius Commission. For animal health, it identifies the International Office of Epizootics. For plant health, it identifies the International Plant Protection Convention (IPPC). Several significant issues regarding this framework are:

- Whether all potentially invasive species will be covered by at least one of these international agreements;
- Whether any invasive species will be covered by more than one of them, which will need agreements as to which should be responsible;
- Whether the various agreements are harmonized to treat similar risks in a similar way; *and*,
- Whether international capacity to develop and implement procedures under each agreement is sufficient to ensure equivalent protection against invasive species under all the other agreements.

The IPPC is administered by the Food and Agriculture Organization (FAO). It was established to provide a uniform, scientific approach to controlling the international spread of plant pests. The Convention covers all plant pests, which are defined as organisms that cause an unacceptable (potential) economic impact to plants in some area. Pests may be excluded, or their movement managed, to reduce the economic risks to plants. It is up to the importing country to demonstrate that a potential pest is of economic concern, thus there is a presumption of safety until proven otherwise. Pest status is demonstrated by a pest risk analysis (PRA). The PRA guidelines are under revision, but one of the more recent versions is the April 1999 draft of Pest Risk Analysis for Quarantine Pests.

PRAs can be initiated in three ways: identification of a pathway that presents a potential pest hazard, identification of a pest that may require action, or a review of policies or priorities. Next, the potential pests are evaluated to determine if they need to be regulated. If it is determined that they do not need regulation, the process stops. Otherwise, the potential for entry, establishment and spread is evaluated, and the potential economic impact is assessed. Both direct and indirect pest effects are assessed. The non-commercial impacts, which is difficult to measure in terms of prices etc, can be approximated with an appropriate non-market valuation. The economic evaluation should be in terms of a monetary value, wherever possible.

Next, risk management is proposed to reduce the risk to an acceptable level. The acceptable level of risk may be expressed in a number of ways, such as meeting existing phytosanitary requirements, indexed to estimated economic losses, expressed on a scale of risk tolerance, or compared with the level of risk accepted by other countries.

Potential strengths

1. FAO has a significant program for building the capacity of countries to conduct PRAs and implement effective management to reduce the risks from exotic plant pests. It would be wasteful of limited financial and human resources to attempt to establish another parallel risk analysis structure for invasive species.
2. The connection of IPPC to the SPS Agreement means that if the IPPC is used to evaluate and manage invasive species, its recommendations would probably have widespread and rapid adoption.
3. The flexibility to initiate a PRA based on pathway, organism or policy is excellent.
4. The initial focus of the PRA on problem identification is very useful.

Potential concerns

1. The presumption of safety embedded within the IPPC is a potential problem. We do not have complete scientific information when we carry out risk assessment. This absence of information may make it difficult to disprove the presumption of safety. It will be essential to address explicitly how uncertainty will be incorporated into a PRA.
2. The risks of invasive species will probably not fall equally on everyone. Peoples who depend on local natural resources are more likely to be adversely affected than those with access to external resources. Attention to the distribution of risk, particularly with regard to the most vulnerable people, needs to be added to the PRA process.
3. The focus on economic costs of plant pests will undervalue many of the ecological effects of invasive species. The definition of a pest should be expanded to include other costs, including transformation of the ecosystem and the loss of native species.

These changes might take many years for the IPPC to implement, partly because the science base that underlies the need to make these changes is not organized. In addition, effective implementation of procedures to reduce the risks of invasive species may require close coordination with present quarantine and plant protection services. Consequently, rapid engagement with these services may be needed to ensure that the risks of invasive species are reduced worldwide.

Convention on Biodiversity

The Convention on Biodiversity (CBD) was drafted in 1992 and has been ratified by several countries, but not by the United States. The CBD is an international agreement to conserve biological diversity for the benefit of present and future generations. It identifies numberous measures to enable the signatories to accomplish this goal, including protection of indigenous biodiversity by restricting its use and protecting it against external threat. It directly relates to the risk of invasive species by specifying in Article 8(h) that the contracting parties shall, as far as possible and as appropriate, prevent the introduction of alien species which threaten ecosystems, habitats or species, and if they should be introduced, to control or eradicate them. In addition, in the Preamble of the CBD, there is a commitment to the Precautionary Principle. This specifically states that where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should be not be used as the reason for postponing measures to avoid or minimize such a threat.

While the CBD provides strong principles under which invasive species can be regulated, it lacks the detailed specificity of the IPPC and the PRA Protocols developed to implement these principles. Moreover, the capacity to implement these principles is weak or absent in most countries, including the United States. Consequently, there must be a considerable effort expended before we can make widespread use of these principles to reduce and manage risks from potential invasive species.

Comparison of the SPS agreement and the CBD for exotic species

Burden of proof

The burden of proof is perhaps the most significant difference between the SPS Agreement and the CBD. The SPS Agreement allows the restriction of movement or regulation of invasive exotics only when it is necessary and scientifically justified. If the Biosafety Protocol were to be extended to invasive exotics, the CBD would allow restriction of movement or regulation as appropriate to avoid or minimize potential adverse effects, even if there were no scientific proof. Although this difference appears stark and unresolvable, there is room for interpretation. As indicated above, all risk analyses of potential invasive species, whether conducted under the SPS Agreement or not, lack scientific certainty. Thus, this difference between the agreements may hinge on an interpretation of what constitutes scientific justification and how it is to be realized.

Uncertainty

There appears to be a considerable difference between the agreements on how uncertainty affects decision-making. Under the SPS Agreement, decisions can be taken when adequate scientific knowledge is not available, but such decisions are provisional. It is necessary to acquire the needed scientific information within a reasonable period of time. Under the Biosafety Protocol, decisions taken in a situation of scientific uncertainty can be final. While several disputes have provided an interpretation about what is ‘a reasonable period’ of time to acquire missing information, (a developed country with the resources to gather the information must start to gather it within a couple of years of making the provisional decision), it is clear that countries lacking in capacity will not be penalized because they cannot afford to gather the information.

On the other hand, although the Biosafety Protocol indicates that precautionary decisions can be final, in practice, if new contradictory information were to become available, the decision would probably be reversed. This would make all precautionary decisions provisional on future contradictory information. Thus, the main difference between the two agreements may be the requirement of the SPS Agreement to gather supporting scientific information, and the timeline for gathering it. Both of these regulations which are absent from the CDB.

Implementation

The SPS Agreement is implemented through the IPPC, which evaluates plant pest risks from alien invasives. The CBD is not yet implemented, but it will evaluate the risk of alien invasives to biological diversity and sustainable use of natural resources. This will include ecosystem properties and habitat quality, neither of which is explicitly evaluated under the IPPC-PRA’s. Clearly, the mandate under IPPC does not exclude evaluating risks to the ecosystem, but detailed methodologies have not yet been developed. Furthermore, the training and capacity-building efforts to conduct risk analysis under IPPC cannot be matched by CBD. The conclusion is that some accommodation between the SPS Agreement and the CBD must be found within the IPPC and its PRA protocols. This will probably require substantial compromise. It will be necessary to develop risk analysis models for evaluating ecosystem and habitat risks before such an accommodation can be expected.

CONCLUSION

1. Exotic species have caused tremendous environmental damage, degraded human health and interfered with many human activities. Entire ecosystems have been transformed, native species have been extirpated, people have become sick and died, and livelihoods and ways of life have been eliminated. These adverse effects are expected to increase in the future.
2. Many of the environmental risks of exotic species have not been identified in ways that make them amenable to risk analysis. While transformation of ecosystems and loss of native species are easy to recognize after they happen, it is difficult to predict which exotic species may increase these risks. It will be necessary to involve the many people affected by exotic species in the process of identifying risks.
3. A risk assessment model for intentional (deliberate) releases of exotic species needs to be developed and implemented. This model is likely to begin with the identification of a species. From a regulatory perspective, a database can be helpful to determine whether an exotic species has caused environmental damage in the past, it is also useful to know whether its risks have been and, if so, what kind of damage assessed elsewhere, and the results of such an assessment.
4. A different risk assessment model for accidental (inadvertent) releases of exotic species needs to be developed and implemented. This model could begin with the identification of a dispersal pathway. From a regulatory perspective, a database could be helpful in determining the kinds of species that are associated with the dispersal pathway, the history of damage by any of these species, the history of adverse environmental effects associated with the dispersal pathway or similar pathways, and whether a risk assessment has been conducted on the pathway elsewhere and the results of such an assessment.

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