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International cooperation in the solution to trade-related invasive species risks[a]

Charles Perrings,[1] Stas Burgiel,[2] Mark Lonsdale,[3] Harold Mooney,[4] and Mark Williamson[5]

[1]School of Life Sciences, Arizona State University, Tempe, Arizona, USA. [2]Global Invasive Species Programme, Alexandria, Virginia, USA. [3]CSIRO Entomology, Black Mountain Laboratories, Canberra, Australian Capital Territory, Australia. [4]Department of Biological Sciences, Stanford University, Stanford, California, USA. [5]Department of Biology, University of York, York, UK

Address for correspondence: Charles Perrings, EcoSERVICES Group, School of Life Sciences, Arizona State University, PO Box 874501, Tempe, AZ 85287, USA. Charles.Perrings@asu.edu

In this paper, we consider the factors behind the growth of invasive species as a global problem, and the scope for international cooperation and coordination in addressing that problem. This is limited by the terms of the various international agreements governing trade, health, and biodiversity. The default strategy in most cases has two parts: border protection and the control of or adaptation to introduced species that have escaped detection at the border. Most invasive species policy involves unilateral national defensive action as opposed to coordinated international action. We argue that an important part of the solution to the problem lies in global coordination and cooperation in the management of both pathways and sanitary and phytosanitary risks at all scales. More particularly, because invasive species are an externality of trade, transport, and travel that involve public goods, they require collective regulation of international markets that goes beyond that admitted under the World Trade Organization's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures. We argue that it is important to bring that agreement into conformity with the International Health Regulations (IHR), and to develop an international mechanism to generate and disseminate information on invasive species risks and their impacts.

Keywords: invasive species; trade; international agreements

Introduction

The dramatic acceleration in the number of species introductions, the consequences of this trend for human livelihoods and well-being, and the options for dealing with it are all closely related to a single trend: the growth and ever closer integration of the global economy. The dispersal of human pests and pathogens has been a consequence of the movement of people for millennia. Over the last 50 years, however, the main driver behind biological invasions is the growth of trade. Although climate change alters the natural range of species, the growth of trade affects the number and frequency of new introductions, and hence the likelihood that species will establish and spread.[3,4]

This paper considers both the factors behind the growth of invasive species as a global problem, and the scope for international cooperation and coordination in addressing that problem. This is limited by the terms of the various international agreements governing trade and its impacts on human, animal, and plant health, and especially by the agreement that most directly deals with trade-related invasive species risks, the Sanitary and Phytosanitary (SPS) Agreement. The default strategy in most cases has two parts: border protection and the control of or adaptation to introduced species that have escaped detection at the border. As a result, most invasive species policy involves unilateral national defensive action as opposed to coordinated international

[a]This paper summarizes the recommendations for the management of international invasive species risks in Perrings C., H. Mooney & M. Williamson (Eds), *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*, Oxford University Press, Oxford. In doing so it draws heavily on two chapters in that volume.[1,2]

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action. We conclude that this is not sufficient, and that the solution to the problem requires more proactive global coordination and cooperation in the management of both pathways and sanitary and phytosanitary risks at all scales.

More particularly, we argue that the tight linkage between invasive species risks and the closer integration of the world economic system means that the best strategy for dealing with the problem involves international action: (a) to internalize what are potentially major externalities of world trade and (b) to address the provision of a global public good. We also argue that the uncertainty which follows from the rapid evolution of the global system—for example, that surrounding emerging zoonotic diseases—demands a strategy that is at once precautionary (that it protects the system while allowing learning about the consequences of novelty) and cost-effective (in practice, that it does not involve the costs associated with unnecessary restriction of trade or travel). Although precaution is a feature of existing instruments, such as the SPS Agreement, we note that it is an option that is effectively only available to that subset of wealthier countries that is capable of scientifically supporting a precautionary argument and that this defect increases global exposure to invasive species risks.

We claim that controlling the movement and spread of invasive species requires coordination across countries to identify common threats, implement prevention or management measures, and ultimately to ensure that new outbreaks do not breach the weakest points in the biosecurity system. Currently, very few countries have the resources, the biogeographical conditions, and the institutional, statutory and regulatory environment to mount effective defenses against invasive species (New Zealand and Australia are commonly cited counter examples, but even here, there are concerns about biosecurity capability and institutional design). For most countries, cooperative efforts at the regional and global level offer a more cost-effective solution. Yet, it remains the case that the default strategy is still national defense, not international cooperation.

Ecological and economic dimensions of the problem

Our starting point is that because inspection, interception, quarantine, eradication, and control all have an opportunity cost that needs to be balanced against the gains of those actions measured in terms of avoided damage, the problem of invasive species is as much an economic problem as an ecological problem. This implies that it is not sufficient to understand only the ecological risk factors in the spread of introduced species (the plasticity or generalism of introduced species, and the effects on the host system of fragmentation, disturbance, biodiversity loss, bioclimatic distance from the source country, as well as the existence of predators or competitors of the introduced species). Nor is it sufficient to understand the ecological consequences of invasions.

The invasibility of ecosystems is a function of both ecosystem type and anthropogenic disturbance. Some ecosystems are intrinsically more vulnerable to invasions than others, but the vulnerability of all ecosystems tends to increase with anthropogenic fragmentation, disturbance, biodiversity change, and the like.[6] It follows that the same activities undertaken in different ecosystems may have different consequences for the invasibility of those systems. It is accordingly important to understand how management actions affect invasibility, and how this varies between ecosystem types. Habitat loss through land use change may be the most important macro-cause of ecosystem vulnerability, but much less intrusive habitat changes can have similar effects.[7] Interventions that create habitat suited to particular species increase the likelihood that those species will establish and spread if introduced. Symmetrically, interventions that create habitat unsuited to particular species decrease the likelihood that those species will establish and spread if introduced. Indeed, this is the basis not just for conservation, but also for all agriculture, forestry, aquaculture, and for *in situ* sanitary and phytosanitary measures. The increasing incidence of malaria, for example, partly reflects the abandonment of public health strategies aimed at reducing the area of suitable habitat for the vector *Anopheles* spp.[8] Interventions designed to select for one species also make the system more vulnerable to other species—competitors, predators, pathogens, symbionts, or commensals—associated with the targeted species. So, for example, the production of particular crops makes agricultural systems more vulnerable to weeds (competitors) and to crop pests and diseases (predators).[4]

The consequences of bioinvasions include both direct and indirect impacts. The damage due to pathogens, for example, involves both the direct harm to the infected species and the indirect effects of changes in either their abundance or behavior. In some cases, these include the extirpation or extinction of species,[9,10] as is currently the case with numbers of frogs, toads, newts, salamanders, and caecilians.[11] Invasive species are also important for the effect they have on the functioning of ecosystems, often by displacing or disrupting existing functional groups. In particular cases, this may affect the capacity of the system to absorb anthropogenic and environmental stresses and shocks without losing resilience.[12–14] Maintenance of functional diversity, in particular, supports the provision of ecosystem services over a range of environmental conditions.[15–18] So while the introduction of invasive pests may not immediately affect the production of ecosystem services, it can make the system less able to cope with future variation in environmental conditions.

Specific ecological impacts that have potentially significant economic consequences include the fact that invasive species can act as keystone species, fundamentally changing both ecosystem structure and function. In fact, most invasive species differ from native species in some trait behavior or function (e.g., nitrogen fixation), inducing change through a variety of mechanisms including exploitation competition (e.g., resources), interference competition (e.g., allelopathy), and direct predation, herbivory, and parasitism.[19,20]

This can then affect ecosystem services, the benefits that people derive from ecosystems, at four levels: (1) species, (2) communities, (3) ecosystems, and (4) the atmosphere.[21,22] At the species level, for example, competition can lead to the decline or loss of economically valuable species for food, fiber, forage, fuel, and medicine. When invasions result in extinctions, there is also a loss of option value—the opportunities forgone as a result of loss of evolutionary or exploitation potential.[23] At the community level, invasions can lead to a loss of both amenity value and function (e.g., kudzu in the southeastern United States), or can disrupt mutualisms, compromising pollination, and pest control services for agriculture.[24] Finally, invasions can change the physical environment by increasing soil salinity[25,26] or through allelopathy.[27]

At the ecosystem level, invasions can alter trophic interactions and water quality (e.g., golden apple snail[28]), nutrient cycling, and fire frequencies (e.g., *Myrica faya* in Hawaii[29]), hydrological cycles through high evapotranspiration rates, by lowering the water table, and by changing the timing and magnitude of runoff (e.g., Tamarisk in southwestern United States;[25] acacias and pines in South Africa[30]). At the level of the atmosphere, invasive species may affect the composition of the atmosphere by changing rates of carbon dioxide sequestration, emitting gases, or volatile organic compounds that have adverse health effects.[22]

Invasive species affect populations, community interactions, ecosystem processes, and abiotic variables. The cascading effect of biological invasions can lead to impacts on multiple ecosystem services. Their effects on the production of food, fiber, and fuel both directly and indirectly, for example, through effects of pests on pollinating insects, may be best known.[31] These have also been calculated in monetary terms in a number of studies.[32,33,34,35] However, they also have impacts on regulating services such as water purification, pest control, natural hazards, and climate mitigation, all essential to fisheries, agriculture, and forestry;[36] and to the fire regime.[37]

To illustrate, Table 1 reports the range of effects of invasive species on ecosystem services in one biome, the fynbos of South Africa. In this case, interactions between invasive *Pinus*, *Hakea*, and *Acacia* species and species have affected the water available both to other species in the system and to human users, making both the ecological and social systems more vulnerable to fluctuations in precipitation.[38–40]

What makes this an economic problem is that these impacts of trade decisions affect the production of things that people care about (they have an opportunity cost) that is ignored by the actors concerned (it is an external effect of the market transactions involved).[54–56] The economic forces that drive the problem of biological invasions include (1) trends in land use that affect the vulnerability or susceptibility of ecosystems; (2) trends in trade, transport, and travel that affect the likelihood of species introductions; and (3) trends in technology that affect species' impacts. Globalization particularly affects the second and third of these, influencing both the species involved in exchanges and the likelihood of their becoming invasive. There is a positive

Table 1. **The impact of woody alien invasive plants on ecosystem services in the Cape Floristic Region, South Africa**[54]

Services impacted	Mechanisms	Positive/ negative	$-value (cost/benefit)	Source/ reference no.
Food	Reduced grazing area; less freshwater for fishing	±		40, 41
Fiber	Timber; flowers and thatching reed	+	$300 million/year from forestry; $1.6 billion/year in value-added wood products; $18 million/year in lost flower and grass earnings	38–40, 42–44
Fuel	Firewood	+	$2.8 million	43–45
Fresh water	Uses more water than native species	−	$1.4 billion in water lost to transpiration; up to 30% of water supply;	39, 43, 46
Medicine	Displace fynbos plants used for drugs and tea; loss of option value (undiscovered medicinal plants)	−	Rooibos tea exports worth $2.1 million (1993)	38, 46
Pollination	Eucalyptus increase honey production; displaced flowers—loss of native nectar	±	$68/ha in lost pollination service—approximately $306 million	38, 48
Climate regulation	More carbon sequestration	+		
Erosion Control	More intense fires result in soil loss with rainwater runoff	−		49–51
Natural hazards regulation	Increased biomass/fuel load; increased runoff following erosion causes flooding	−		40, 51, 52
Aesthetic value	Ornamentals, shade trees; loss of fynbos wildflowers	±		40.
Recreation and tourism	Invasion of dunes has lead to loss of beaches; damage to fynbos ecotourism	−		39, 46, 53
Cultural heritage	Displaces native flora for flower harvesting; disturbs sacred pools; wood used for ceremonies	±		41, 45

Note: Values are in (2001) U.S. dollars.

relationship both between the opening of new markets or trade routes and the introduction of new species, and between the growth in trade volumes (the frequency of introduction) and the probability that introduced species will establish and spread.[57–59] The second relationship reflects the fact that more trade means more propagule pressure.[60,61] The volume and direction of trade turn out to be good empirical predictors of which introduced species are likely to become invasive,[62,3] which countries are the most likely sources of zoonoses,[63,64] and the likelihood of transmission of individual human diseases such as West Nile virus, H5N1 avian influenza, and 2009 A/H1N1 influenza.[65–68]

Costello *et al.*'s study of invasive species risks in San Francisco Bay, for example, shows that the risks associated with imports to the area differ depending on the source of the exports, and the cumulative number of introductions from a particular source depends on the volume of imports.[3] Similarly, Kilpatrick *et al.*'s study of the spread of the avian influenza virus H5N1 found that its spread in Asia and Africa involved both the poultry trade and wild bird movements, whereas transmission to the Americas was due wholly to the poultry trade.[65,69]

Estimates of the economic cost of the ecological damage done by invasive species vary widely. The first estimate of the costs of invasive species by the Office of Technology Assessment of the US Congress was concluded in 1993.[70] Since that time Pimentel *et al.*[32–34] have updated the OTA estimates and extended them beyond the United States. For the agricultural sector, for example, they conclude that invasive species cause damage costs equal to around 50% of agricultural GDP in the United States and Australia, 30% in the UK, but between 81% and 110% of agricultural GDP in South Africa, India, and Brazil. Although their estimates are rough approximations only, they indicate both the wide range in damage costs and their sensitivity to the importance of agriculture to employment and output.[71]

We have indicated that the typical management response is largely centered on efforts to defend national borders against introductions, the eradication of already introduced species where possible, and their control where not. In the absence of reliable estimates of the net benefits of investment in the defensive capabilities of ecosystems themselves, the relative costs and benefits of alternative strategies generally involve a comparison of net benefits of inspection and interception or detection and eradication versus the control of established invaders. Given the evidence for the cost advantage of prevention over later control in the case of most harmful species,[72] many scientists working on the problem are predisposed toward preventive action.[73,74]

However, the optimal choice between mitigation and adaptation does depend on the costs and benefits of each strategy. Polasky has evaluated the choice between inspection (to prevent introduction), detection (to identify and eradicate species that have got past the border but have not yet spread), and control (management of species that have established and spread).[7] The first two correspond to the "prevention" and "early detection and rapid response" options of the U.S. National Invasive Species Council, and both involve the mitigation of risk. He finds that inspection and detection are generally substitutes—that reducing the cost of one of these two strategies will increase the optimal effort devoted to it and reduce the optimal effort devoted to the other. Detection and eradication are complements, but both are substitutes for the control of established populations. He finds that when control is impossible at large population levels, at which point invasions become irreversible, the return to inspection and detection rises sharply.

The costs of inspection, detection, and interception are not, however, independent of actions taken at the international level. Where trading partners exercise lax sanitary and phytosanitary controls, the likelihood of introductions with traded goods is higher than where they are more rigorous. Similarly, vessels that observe the regulations on, for example, ballast water exchange are less of a risk than vessels that do not. More importantly, the risks (and hence the costs) to any one country are lower the greater the international effort taken to contain the risks associated with the transmission of disease or the spread of pests. It follows, that the likelihood that individual countries will fall back on adaptation to or control of established populations is higher, the weaker the set of international measures taken to address the problem.

Three factors influence a country's exposure. First, the more open they are with respect to imports the more likely they are to experience bioinvasions.[58,59] Second, the greater the speed of transport between source and sink countries, the more likely it is that "passenger" species will survive the journey.[75–77] Third, as the volume of trade between countries in bioclimatically similar zones increases, and as scrutiny of imports and exports between countries in such zones decreases, the likelihood that introduced species will successfully spread rises.[78] The evidence that the likelihood of invasive species is positively correlated with bioclimatic matching in source and sink areas is strong,[79] although climate matching studies of invading pests also show that the area invaded covers a wider climatic spectrum than the climates of the native range. This is related to the trend toward regional trade agreements (RTAs). These are bilateral or multilateral trade agreements to reduce barriers to the movement of commodities and people within the area covered by the agreement and include, for example, the European Union and the European Free Trade Association (EFTA), the North American Free Trade Agreement (NAFTA), the Southern Common Market (MERCOSUR), the Free Trade Area of ASEAN, the Association of Southeast Asian Nations (AFTA), and the Common Market of Eastern and Southern Africa (COMESA). Although many RTAs include environmental agreements, one consequence of most has been to reduce the effectiveness of import protection measures applying to trade between member states. Because many involve neighboring states, they facilitate the dispersal of species new to the region between those states.[78] Given these three factors, however, the local problem is exacerbated or not depending on the state on international controls.

The international institutional environment

Because bioinvasions are an externality of international trade, it follows that solutions to the international problem lie in actions to internalize these externalities. This is governed by the institutions responsible for regulating international trade: the World Trade Organization (WTO) and the General Agreement on Tariffs and Trade (GATT), along with supporting agreements such as the SPS Agreement and the Agreement on Technical Barriers to Trade (TBT Agreement). Many other organizations and agreements have a role to play, but this is generally secondary to the GATT. The Convention on International Trade in Endangered Species (CITES), for example, has specific responsibility for endangered species but no mandate within the WTO system—although it has observer status on the WTO's Committee on Trade and Environment. Institutions concerned with the impact of invasive species on the general environment, for example, include the Convention on Biological Diversity (CBD) and its Cartagena Protocol on Biosafety, the Ramsar Convention on Wetlands of International Importance, the Convention on Migratory Species (CMS) along with many other multilateral environmental agreements. Institutions concerned with pathways (transport routes) include the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), and the UN Convention on the Law of the Sea (UNCLOS). Institutions concerned with agriculture, aquaculture, forestry, and fisheries include World Animal Health Organization (OIE), International Plant Protection Convention (IPPC), and the UN Food and Agriculture Organization (FAO) along with its Compliance Agreement and Code of Conduct for Responsible Fisheries. Institutions concerned with human health include the WHO and the International Health Regulations.

A number of these bodies have overlapping mandates. The CBD, FAO, and WTO, for example, have broad and frequently overlapping coverage. In other instances, no institution has explicit responsibility. The invasive species risks of tourism, emergency aid and development assistance, military activity, and interbasin water transfers are all cases in point. The CBD has identified a number of gaps and areas of inconsistency induced by overlapping responsibility at the international level including, for examples, animals that are not plant pests (pets, aquarium species, live bait, live food), marine biofouling, tourism, emergency aid and development assistance, military activities and interbasin water transfers and canals, marine aquaculture, and civil air transport. Similarly, the World Animal Health Organization's (OIE) focus on diseases related to livestock and other commercially valuable animal species neglects both interactions between species, and the wider and longer-term effects of species dispersal. The CBD's ninth Conference of the Parties prioritized invasive species, and specifically such orphan species, but the gaps remain.[82]

An additional problem is the legal effect of the decisions reached by different agreements. Because the CBD is a "soft law" convention, it has no enforcement mechanisms to ensure compliance. Its resolutions take the form of nonbinding guidelines, principles, and frameworks. Other international institutions are less limited in what they can do. For example, the IPPC and OIE have developed international standards in their respective areas of expertise that are recognized as compatible with international trade rules under the WTO's SPS Agreement. This means that a country implementing an IPPC or OIE standard is protected from the WTO's dispute settlement process. At the same time, the options open under the GATT are limited. Successive rounds of negotiation of the Agreement have consistently rejected the use of tariffs to address international trade externalities. So although the "polluter pays" principle might be thought to apply to international market transactions in the same way that it applies to market transactions within national boundaries, the tariff option is not available to GATT signatories. National governments can use incentive mechanisms to encourage importers to adopt appropriate sanitary and phytosanitary measures, or can levy charges for inspections, but they cannot use tariffs to tax their trading partners.

Solving the international problem: learning from human health

So what can be done? Under the WTO and its constituent agreements, countries currently have the right to take trade-restrictive actions to protect food safety, animal or plant health. There is, however, no mechanism to address the collective risks posed by the international trading system. The position with respect to human health is rather different. Indeed, the 2005 International Health Regulations administered by the World Health Organization (WHO) mandate both coordinated and cooperative international action to address human health risks. We consider the implications of this model for other invasive species risks. We note that all of the main multilateral environmental agreements require states to ensure that they are not themselves a source of risk to others. Article 3 of the Convention on Biological Diversity (1993), for example, asserts that "States have . . . the sovereign right to exploit their own resources pursuant to their own environmental policies, *and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.*" Article 14 goes further, requiring states to notify others of events that are likely to affect biodiversity of other state or areas beyond national jurisdiction. Where damage to other states is "imminent or grave," states are notionally required to take action to minimize the damage and the agreement does encourage international cooperation to supplement national efforts. Given the nonbinding nature of the agreement, however, this is weak.

In what follows, we argue for a strategy for dealing with invasive species risks that does not rely as heavily on the unilateral actions of source and sink states, but that leaves a role for collective multilateral action. In other words, we argue for the need to go beyond the traditional defensive measures allowed under the SPS Agreement, and in the direction of the cooperative action allowed under the International Health Regulations.[81] Because a review of the SPS Agreement is on the agenda for the beleaguered Doha round of the GATT there is an opportunity to do this.

The main problem with the existing international arrangements is that while Article XX of the GATT, and the SPS Agreement that implements that Article, allow countries to protect themselves against the invasive species risks of trade, they do so under a very restrictive set of conditions. In particular, invasive species risks are addressed as bilateral trade issues. The interception of pests or pathogens by one country reduces the likelihood that it will infect/reinfect its trading partners with the same pest or pathogen. But because inspection (the knowledge it generates) and interception (the protection it offers the wider community) are international public goods, they will be undersupplied if left to individual countries. This is not efficient.

The treatment of emerging infectious human diseases under the IHR is very different from the treatment of other potentially invasive species under the SPS Agreement.[81] We argue that a significant step toward development of mechanisms to address invasive species risks might be achieved by bringing the International Health Regulations and the SPS Agreement into conformity with one another. The two instruments currently offer very different levels of protection to the global community. The aims and scope of the IHR are "to prevent, protect against, control and provide a public health response to the international spread of disease in ways that are commensurate with and restricted to public health risks, and which avoid unnecessary interference with international traffic and trade" (Article 2).[81] The aims of the SPS Agreement, by contrast, are to ensure that the defensive measures taken by members to protect their own human, animal, and plant health do not constitute a barrier to trade (Article 2).[82]

The difference is reflected in the contrasting roles of the WHO and the OIE in disease outbreaks. During the SARS outbreak in 2003, for example, the WHO's Global Outbreak Alert and Response Network (GOARN) was mobilized to support international teams in China, Vietnam, and Singapore. The teams were drawn from 15 countries, and worked with national authorities on case management, infection control, surveillance, laboratory testing, and epidemiological investigation. The WHO also coordinated actions by Médecins Sans Frontières, the United States, Australia, Japan, and France to supply approved protective and clinical management equipment. There are no analogous responses from the OIE to animal or plant disease outbreaks. Indeed, its role is still regarded as being to provide national governments with information that will enable them to determine the appropriate response. Although there is agreement between international organizations that a stronger coordination function is important—the OIE and the UN Food and Agricultural Organization (FAO) signed an agreement in 2004 on a "Global Framework for the Progressive Control of Transboundary Animal Diseases"—the focus in disease outbreaks remains on informing national response. To change the way that international animal and plant diseases are addressed requires reform at multiple scales involving interactions between and within intergovernmental organizations and national governments, and ultimately involving reform of national implementing legislation. But enhancing the coordination role of the OIE by extending the SPS Agreement to offer the same protection against international risks to animal and plant health as the IHR would be an important first step.

There is a second difference between the IHR and the SPS Agreement that would also be worth addressing. It lies in the commitment that member states make under each agreement to building the capacity of developing countries to discharge their responsibilities under the agreement. Once again, the IHR embodies a far more constructive approach. It both imposes reporting obligations on countries, and requires that they develop the capacity to detect, assess, notify, and report disease events within 5 years (Article 5(1)).[81] At the same time, however, it imposes an obligation on the WHO to support this. There is nothing equivalent for the SPS Agreement. That agreement does include a commitment "to facilitate the provision of technical assistance to . . . developing country Members, either bilaterally or through the appropriate international organizations" (Article 9(1)), and encourages developed countries to consider providing such technical assistance.[82] This is much weaker than the obligation on the WHO under the IHR. The information needed to enhance national or regional capacity is currently provided by national invasive species databases, the work in the Americas by IABIN and Europe by DAISIE, and at the international level by CABI, ISSG, and GISIN. These do not have the IGO/governmental status of the CDC, OIE, and IPPC, but they do provide services that could be more productively exploited in developing local capacity. There are also examples of individual countries engaging in SPS capacity building. Australia's support of the Southeast Asia Foot and Mouth Disease Campaign—a coordinated campaign to control Foot and Mouth Disease by eight countries in the ASEAN region—is a case in point.

The underlying problem that needs to be addressed through collective action is that the control of species that threaten the wider community is a public good. An inspection and interception policy that protects people against invasive pathogens provides benefits that are neither "rival" nor "exclusive." If one state benefits from the protection offered by the policy, it neither affects the costs of the policy nor the benefits it offers to other states. As with any public good, however, each state has an incentive to free ride on the efforts of others. The special difficulty with invasive species control is that it is a very particular kind of public good. The benefits offered by any inspection and interception regime to all states are only as good as the benefits offered by the least effective state. Public goods of this sort are "weakest link" public goods. It only takes one country's failure to monitor, detect, or contain an infectious disease to compromise the control efforts of all other countries, so the safety of all lies in the hands of the least reliable state.[82] This is the motivation for buttressing the capacity of countries to comply with the IHR through the support offered by the WHO. We need something analogous for other invasive species besides human diseases.

We have elsewhere suggested the need for a coordinated international response to the monitoring problem that would build on the experience of the Center for Disease Control (CDC) in monitoring and reporting on human diseases.[83,2] Specifically, an international body with responsibility for invasive species generally, that would be charged with developing and maintaining a database that would include the species-level data provided by the CDC, the OIE, the IPPC and other invasive species databases. Aside from monitoring trends and providing risk assessments and recommendations for action, they argued that such an organization should be able to coordinate responses to invasive species threats in poorer countries. This could also be a way of enhancing the effectiveness of the current system, in that it would provide low-income countries with the information needed to protect their citizens under the existing SPS Agreement.

That agreement requires that sanitary and phytosanitary measures should not act as restriction on international trade,[82] that they be based on scientific principles, and that they should not persist in the absence of sufficient scientific evidence. The requirement for sufficient scientific evidence is one reason why SPS Agreement is seldom used by low-income countries. A CDC-equivalent (in addition to the existing Standards and Trade Development Facility) might provide low-income countries with the monitoring and scientific support needed to make the current system work.

More generally, a mechanism to generate and disseminate information on invasive species risks would: (1) enable the more effective use of defensive measures allowed under the SPS Agreement, especially by developing countries; (2) facilitate the coordination of actions by different international institutions; and (3) support cooperative international action on invasive species that may cause widespread harm to animals and plants, and hence damage to the ecosystem services they generate.

Solving the international problem: cooperating at what scale?

The most important multilateral bodies for the problem of invasive species may be the IHR, the SPS Agreement, and the three agencies that support the SPS Agreement—the Codex Alimentarius Commission for food safety, the International Office of Epizootics for animal health, and the International Plant Protection Convention for plant health. But the point has also been made that many other international bodies have remits that overlap with these agreements. It is also the case that not all invasive species problems are global. Indeed, the number of host systems that particular species may successfully invade is generally quite limited. It follows that the level at which international cooperation is required will vary from one case to another. We remarked earlier that a dominant characteristic of the developing world trade system is the increasing number of Regional Trade Agreements (RTAs)—of which there are more than 400 either current or pending. These agreements are part of the problem. However, they are also potentially a part of the solution, because they provide a framework for addressing the invasive species problem at a regional level.

The development of RTAs is part of the problem of invasive species for two reasons. One is that RTAs are designed to lead to increased volumes of trade and can result in lower levels of inspection between countries in which bioclimatic conditions are broadly similar, and hence in which the risk that introduced species will establish, naturalize, and spread is high. There is, for example, some evidence that the North American Free Trade Association (NAFTA) has facilitated the spread of species within the free trade area.[78] Second, the promotion of trade in agricultural products between regions in which resources for the detection and control of potentially invasive species are weak must be a concern.

Against this is the fact that many RTAs explicitly address the environmental risks of regional trade. Indeed, cooperation within RTAs may be an important part of the solution to biological invasion externalities and the free rider problems attaching to the control of nonindigenous species. If there are economies of scale or transboundary externalities, regional cooperation has been argued to provide one answer.[84] In some cases, the environmental agreements within RTAs can help encourage compliance with environmental laws. So, for example, the NAFTA Commission for Environmental Cooperation exists to ensure that member states do not seek a trade benefit or attract inward investment by failing to comply with environmental laws. Similarly, the environmental chapter of the U.S.–Singapore Free Trade Agreement requires both countries to enforce their environmental laws, and includes fines for noncompliance.[77]

A second role of the environmental agreements is to harmonize environmental standards between member states of the RTA. The South American Common Market (MERCOSUR), for example, includes an environmental working group charged with eliminating the use of environmental barriers to trade, promoting "upward harmonization" of environmental management systems, and securing cooperation on shared ecosystems. Indeed, many of the main South-South RTAs—MERCOSUR, the Andean Pact, the Common Market for Eastern and Southern Africa (COMESA), the Southern African Development Community (SADC), the ASEAN Free Trade Area (AFTA), and the Caribbean Community (CARICOM)—include agreements on environmental standards.[85]

Most importantly, RTAs may make it possible for invasive species risks to be managed at the level of the group. There are several options. First, prevention and control efforts can focus on the main hubs for moving goods and people into and out of a region. Quarantine and preborder controls focused on strategic points can benefit all member states. Because of the weakest-link nature of the problem, the entry points into a region with the weakest monitoring, inspection, management, or prevention affect the vulnerability of the whole region. However, for the same reason, collective action to reinforce weak points can reduce the costs of defensive measures for the whole region. More particularly, regional initiatives and institutions can play a role in training and capacity development, exchanging experiences across countries and regions, and providing regional centers of expertise for risk assessment.

There are examples of regional strategies on invasive species. The European Strategy on Invasive Alien Species under the Bern Convention and the regional Guidelines for Invasive Species Management in the Pacific and the Caribbean Regional Invasive Species Intervention Strategy are cases in point. The experience of the latter is instructive. Four different institutions are collaborating to support both national and region-wide efforts: the South Pacific Regional Environment Programme (SPREP), the Secretariat of the Pacific Community (SPC), the Pacific Invasives Initiative (PII), and the Pacific Invasives Learning Network (PILN). SPREP is the Pacific region's major intergovernmental organization charged with protecting and managing the environment. It has the authority to convene the region's governments to help coordinate strategies and policies to address the environmental aspects of invasive species, and has used this to develop a regional strategy (and associated funding program). SPREP grew out of the SPC and the two bodies maintain close ties and coordination in their activities. The SPC is the Pacific's oldest regional intergovernmental organization and serves as a technical advisory and implementation body to assist with social, land, and marine resource issues. Its work on invasive species focuses on quarantine-, agriculture-, and aquaculture-related issues, including management, training, and policy/legislation with some overlap on the environmental side.

The PII is a nongovernmental organization composed of a partnership of eight organizations that mounts demonstration projects, from the initial planning stages to implementation to exchange of lessons learned. PII therefore has a very technical orientation on invasive species eradication, control and management, which includes ensuring that skills related to project development and implementation are shared across the Pacific. The Pacific Invasive Learning Network (PILN) is a partnership of several national, regional, and international organizations, which serves approximately 14 interagency and multi-stakeholder teams from Pacific Island countries and territories. PILN's focus is on developing in-country capacity through networking and cross-team collaboration, skill and resource sharing, links to technical expertise, and information exchange. Most other regions also have bodies that serve some of these functions, although the breadth of activity observed in the Pacific is unusual.

Such regional networks provide a mechanism for countries to coordinate on priorities or threats. They can also help build and support capacity, particularly in areas where it is unlikely that single countries will ever be able to develop independent, fully-fledged biosecurity systems. Nevertheless, regional initiatives and RTAs are limited in what they can achieve for the protection of the wider community, and their effectiveness is constrained by the terms of other international conventions and institutions.

Conclusions

The rapid increase in the number of harmful invasive species in most countries indicates that current attempts to mitigate those risks within national borders—defensive measures for inspection and interception at the port of entry, and detection and eradication of new introductions beyond the port of entry—are not keeping up with the rate of introductions. Indeed, some major conservation organizations have turned their back on the issue of invasive species as too hard to handle. Of course it is possible to strengthen the effectiveness of defensive measures by individual countries—whether through standard inspection and interception strategies, or any one of a number of market-based mechanisms proposed for the purpose[57,86,87] However, defensive mechanisms alone are not sufficient. Because the risks facing "sink" countries depend on the capacity of "source" countries to undertake internal sanitary and phytosanitary measures, and because many emergent pests and pathogens originate in areas where that capacity is limited, there is a need to build both capacity and commitment in exporting countries to reduce the risks they pose to others. Bilateral trade agreements can be useful in raising sanitary and phytosanitary standards in exporting countries, and the standards generated by the Codex Alimentarius Commission for food safety, the International Office of Epizootics for animal health, and the International Plant Protection Convention for plant health are a reasonable starting point for that.

However, this largely ignores the costs born by all countries as a result of the fact that the control of invasive species is an international public good, and that every country has an incentive to free ride on the contributions of every other country. Bilateral and regional trade agreements do have the potential to improve the standards applying to bilateral and regional trade, but they necessarily neglect the costs or benefits imposed on third parties. It is not accidental that so many introductions of pests and pathogens involve reinfection from third parties.

Our main recommendation follows from this observation. We argue that it is important to bring the SPS Agreement into conformity with the IHR in recognition of the global nature of some trade-related invasive species risks. The point here is that while some invasive species issues are highly localized in their effects, and therefore best dealt with at a local level, many others are not. This is especially true of infectious diseases spread through international trade that have the potential to spread globally. However, there are many other cases where the unilateral and bilateral arrangements allowed under the SPS Agreement are inappropriate. In these cases, international collective action offers not only the scope to manage international or global vectors, but also the capacity to mobilize resources to strengthen the weakest links in the chain and to enable individual countries to exploit the unilateral defensive measures currently allowed by the SPS Agreement. The establishment of a mechanism to monitor, evaluate, and disseminate information on emerging invasive species risks would be valuable here. So too would the establishment of a fund to replicate the role of the WHO in building local capacity and in coordinating and implementing rapid responses.

The two most urgent aspects of the invasive species problem that need to be addressed both relate to the public good nature of the problem. The fact that the control of many pests and pathogens is a "weakest link" public good demands measures such as mechanisms to build capacity in low-income countries, and to finance control efforts in those countries, to raise the capacity of the countries least able to monitor, evaluate, and manage invasive species risks. The fact that global monitoring, assessment, evaluation, and dissemination is a "best shot" public good supports the notion that wealthier countries should invest in the development of a CDC-like mechanism to generate the information needed by all countries. Although this should build on the monitoring undertaken in specific areas by existing bodies, its primary value would be in the integration of different kinds of data.

Currently, most countries incur large costs in terms of output lost to pests and pathogens, compromised human, animal, and plant health, impacts on ecological functioning and ecosystem services, along with the costs of inspection, interception, eradication, control, and other sanitary and phytosanitary efforts. Individual country expenditure on invasive pests and pathogens is larger than that on almost any other environmental problem. Yet because countries are authorized by existing agreements to neglect many of the external costs of their actions, they do not take these into account in developing their own invasive species management strategies. There are solutions to the problem, however, and the most attainable of these involve the extension of the remit for collective action to contain the spread of destructive pests and pathogens within the SPS Agreement. There are certainly no easy routes to international cooperation, but the difference between the IHR and SPS Agreement suggests that the prospect of extreme losses is a powerful incentive to cooperate

Conflicts of interest

The authors declare no conflicts of interest.

References

1. Perrings, C., H. Mooney & M. Williamson. 2010. The problem of biological invasions. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 1–18. Oxford University Press. Oxford.
2. Perrings, C., S. Burgiel, M. Lonsdale, *et al.* 2010. Globalization and bioinvasions: the international policy problem. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 235–249. Oxford University Press. Oxford.
3. Costello, C., M. Springborn, C. McAusland & A. Solow. 2007. Unintended biological invasions: Does risk vary by trading partner? *J. Environ. Econ. Manage.* **54:** 262–276.
4. Perrings, C., E. Fenichel & A. Kinzig. 2010. Globalization and invasive alien species: trade, pests, and pathogens. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 42–55. Oxford University Press. Oxford.
5. Beale, R., J. Fairbrother, A. Inglis & D. Trebeck. 2008. One biosecurity – a working partnership. Independent review of Australia's quarantine and biosecurity arrangements. Report to the Australian Government, Canberra, ACT. http://www.quarantinebiosecurityreview.gov.au/report_to_the_minister_for_agriculture_fisheries_and_forestry
6. Pyšek, P., M. Chytrý & V. Jarošík. 2010. Habitats and land use as determinants of plant invasions in the temperate zone of Europe. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 66–82. Oxford University Press. Oxford.
7. Polasky, S. 2010. A model of prevention, detection, and control for invasive species. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 100–109. Oxford University Press. Oxford.
8. Khasnis, A.A. & M.D. Nettleman. 2005. Global warming and infectious disease. *Arch. Med. Res.* 36, 689–696.
9. Williamson M. 1996. *Biological Invasions*. Chapman and Hall, London.
10. Glowka, L., F. Burhenne-Guilmin & H. Synge. 1994. *A Guide to the Convention on Biological Diversity*. IUCN, Gland, Switzerland.
11. Daszak, P. & A.A. Cunningham. 1999. Extinction by infection. *Trends Ecol. Evol.* **14:** 279.
12. Kinzig, A.P., P. Ryan, M. Etienne, *et al.*. 2006. Resilience and regime shifts: assessing cascading effects. *Ecol. Soc.* **11:** article 13 [online].
13. Walker, B.H., L.H. Gunderson, A.P. Kinzig, *et al* 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecol. Soc.* **11:** 13. [online] URL: http://www.consecol.org/vol11/iss1/art13/.
14. Walker, B.H., C.S. Holling, S.R. Carpenter & A.P. Kinzig. 2004. Resilience, adaptability, and transformability. *Ecol. Soc.* **9:** 5. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5.
15. Loreau, M., N. Mouquet & A. Gonzalez. 2003. Biodiversity as spatial insurance in heterogeneous landscapes. *Proc. Natl. Acad. Sci.* **22:** 12765–12770.
16. Naeem, S. & J.P. Wright. 2003. Disentangling biodiversity effects on ecosystem functioning: deriving solutions to a seemingly insurmountable problem. *Ecol. Lett.* **6:** 567–579.
17. Reich, P.B., D. Tilman, S. Naeem, *et al.* 2004. Species and functional group diversity independently influence biomass accumulation and its response to CO2 and N. *Proc. Natl. Acad. Sci.* **101:** 10101–10106.
18. Hooper, D.U., F.S. Chapin III, J.J. Ewel, *et al*. 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* **75:** 3–35.
19. Vitousek, P.M. 1990. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. *Oikos* **57:** 7–13.
20. Crooks, J.A. 2002. Characterizing ecosystem-level consequences of biological invasions the role of ecosystem engineers. *Oikos* **97:** 153–166.
21. Levine, J.M., M. Vilà, C.M. D'Antonio, *et al*. 2003. Mechanisms underlying the impacts of exotic plant invasions. *Proc. R. Soc. Lond. B* **270:** 775–781.
22. Charles, H. & Dukes, J.S. 2007. Impacts of invasive species on ecosystem services. In *Biological Invasions. Ecological Studies*. W. Nentwig, Ed.: **193:** 217–237. Springer-Verlag Berlin, Germany.

23. Perrings, C., M. Williamson & S. Dalmazzone, Eds. 2000. *The Economics of Biological Invasions*. Edward Elgar. Cheltenham.
24. Traveset, A. & D.M. Richardson. 2006. Biological invasions as disruptors of plant reproductive mutualisms. *Trends Ecol. Evol.* **21:** 208–216.
25. Zavaleta, E. 2000. The economic value of controlling an invasive shrub. *Ambio* **29:** 462–467.
26. Vivrette, N.J. & C.H. Muller. 1977. Mechanism of invasion and dominance of coastal grassland by Mesembryanthemum crystallinum. *Ecol. Mongr.* **47:** 301–318.
27. Orr, S.P., J.A. Rudgers & K. Clay. 2005. Invasive plants can inhibit native tree seedlings: testing potential allelopathic mechanisms. *Plant Ecol.* **181:** 153–165.
28. Naylor, R.L. 1996. Invasions in agriculture: assessing the cost of the Golden Apple Snail in Asia. *Ambio* **25:** 443–448.
29. Mack, M.C. & C.M. D'Antonio. 1998. Impacts of biological invasions on disturbance regimes. *Trends Ecol. Evol.* **13:** 195–198.
30. Le Maitre, D.C., B.W. van Wilgen, R.A. Chapman & D.H. McKelly. 1996. Invasive plants and water resources in the western Cape Province, South Africa: modeling the consequences of a lack of management. *J. Appl. Ecol.* **33:** 161–172.
31. Pejchar, L. & M. Mooney. 2009. Invasive species, ecosystem services and human well-being. *Trends Ecol. Evol.* **24:** 497–504.
32. Pimentel D., S. McNair, S. Janecka, *et al*. 2001. Economic and environmental threats of alien plant, animal and microbe invasions, Agriculture. *Ecosyst. Environ.* **84:** 1–20.
33. Pimentel D., L. Lach, R. Zuniga & D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. *Bioscience* **50:** 53–56.
34. Pimentel D., R. Zuniga & D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecolog. Econ.* **52:** 273–288.
35. Born, W., F. Rauschmayer & I. Brauer. 2005. Economic evaluation of biological invasions – a survey. *Ecolog. Econ.* **55:** 321–336.
36. Colautti, R.I., S.A. Bailey, C.D.A. van Overdijk, *et al*. 2006. Characterised and projected costs of nonindigenous species in Canada. *Biol. Invasions* **8:** 45–59.
37. Arriaga, L., A.E. Castellanos, V.E. Moreno & J. Alarcón. 2004. Potential ecological distribution of alien invasive species and risk assessment: a case study of buffel grass in arid regions of Mexico. *Conserv. Biol.* **18:** 1504–1514.
38. Turpie, J. & B. Heydenrych. 2000. Economic consequences of alien infestation of the Cape Floral Kingdom's Fynbos vegetation. In: *The Economics of Biological Invasions*. C. Perrings, M. Williamson & S. Dalmazzone, Eds.: Edward Elgar. Cheltenham, UK.
39. Le Maitre, D.C., B.W. van Wilgen, C.M. Gelderblom, *et al*. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecol. Manage.* **160:** 143–159.
40. van Wilgen, B.W. & D.M. Richardson. 2010. Current and future consequences of invasion by alien species: a case study from South Africa. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 183–201. Oxford University Press. Oxford.
41. Richardson, D.M. & B.W. van Wilgen. 2004. Invasive alien plants in South Africa: how well do we understand the ecological impacts? *South African J. Sci.* **100:** 45–52.
42. Cowling, R.M. & D.M. Richardson. 1995. *Fynbos: South Africa's Unique Flora Kingdom*. Fernwood Press, Cape Town, South Africa.
43. Turpie, J.K., B.J. Heydenrych & S.J. Lamberth. 2003. Economic value of terrestrial and marine biodiversity in the Cape Floristic Region: implications for defining effective and socially optimal conservation strategies. *Biol. Conserv.* **112:** 233–251.
44. De Neergaard, A., T. Saarnak, T. Hill, *et al*. 2005. Australian wattle species in the Drakensberg region of South Africa – An invasive alien or a natural resource? *Agric. Sys.* **85:** 216–233.
45. Shackleton, C.M., D. McGarry, S. Fourie, *et al*. 2006. Assessing the effects of invasive alien species on rural livelihoods: case examples and a framework from South Africa. *Human Ecol.* **35:** 113–127.
46. van Wilgen, B.W., R.M. Cowling & C.J. Burgers. 1996. Valuation of ecosystem services: a case study from the fynbos, South Africa. *Bioscience* **46:** 184–189.
47. De Wit, M.P., D.J. Crooks & B.W. Van Wilgen. 2001. Conflicts of interest in environmental management: estimating the costs and benefits of a tree invasion. *Biol. Invasions* **3:** 167–178.
48. Johannsmeier, M.F. & A.J.N. Mostert. 1995. South African nectar and pollen flora. In *Beekeeping in South Africa, 3rd edn, ed. Plant Protection Research Institute Handbook No. 14*. M.F. Johannesmeier, Ed.: 127–148. Agricultural Research Council, Pretoria.
49. Scott, D.F. & D.B. van Wyk. 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *J. Hydrol.* **121:** 239–256.

50. Scott, D.F. & R.E. Schulze. 1992. The hydrological effects of a wildfire in a Eucalypt afforested catchment. *South African Forestry J.* **160:** 67–74.
51. van Wilgen, B.W. & D.F. Scott. 2001. Managing fires on the Cape Peninsula, South Africa: dealing with the inevitable. *J. Med. Ecol.* **2:** 197–208.
52. van Wilgen, B.W. & D.M. Richardson. 1985. The effects of alien shrub invasions on vegetation structure and fire behaviour in South African fynbos shrublands: a simulation study. *J. Appl. Ecol.* **22:** 955–966.
53. Lubke, R.A. 1985. Erosion of the breach at St. Francis Bay, Eastern Cape, South Africa. *Biol. Conserv.* **32:** 99–127.
54. Pejchar, L. & H. Mooney. 2010. The impact of invasive alien species on ecosystem services and human well-being. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 161–182. Oxford University Press. Oxford.
55. Evans, E.A. 2003. Economic dimensions of invasive species. *Choices* 2nd Qtr: 5–9.
56. Eisworth, M.E. & W.S. Johnson. 2002. Managing non-indigenous invasive species: insights from dynamic analysis. *Environ. Resource Econ.* **23:** 319–342.
57. Semmens, B.X. *et al*. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. *Ecol. Prog. Ser.* **266:** 239–244.
58. Vilà M. & J. Pujadas. 2001. Land use and socio-economic correlates of plant invasions in European and North African countries. *Biol. Conserv.* **100:** 397–401.
59. Dalmazzone, S. 2000. Economic Factors affecting vulnerability to biological invasions. In *The Economics of Biological Invasions*. C. Perrings, M. Williamson & S. Dalmazzone, Eds.: 17–30. Edward Elgar. Cheltenham.
60. Simberloff, D. 2009 The role of propagule pressure in biological invasions. *Annu. Rev. Ecol., Evol. Syst.* **40:** 81–107.
61. Casey P., T.M. Blackburn, K.E. Jones & J.L. Lockwood. 2004. Mistakes in the analysis of exotic species establishment: source pool designation and correlates of introduction success among parrots (Psittaciformes) of the world. *J. Biogeogr.* **31:** 277–284.
62. Levine, J.M. & C.M. D'Antonio. 2003. Forecasting biological invasions with increasing international trade. *Conserv. Biol.* **17:** 322–326.
63. Pavlin, B., L.M. Schloegel & P. Daszak. 2009. Risk of importing zoonotic diseases through wildlife trade, United States. *Emerg. Infect. Dis.* **15:** 1721–1726.
64. Smith, K.F., M. Behrens, L.M. Schloegel, *et al*. 2009. Reducing the risks of the wildlife trade. *Science* **324:** 594–595
65. Kilpatrick, A.M., A.A. Chmura, D.W. Gibbons, *et al*. 2006. Predicting the global spread of H5N1 avian influenza. *Proc. Natl. Acad. Sci. USA* **103:** 19368–19373.
66. Kilpatrick, A.M., P. Daszak, S.J. Goodman, *et al*. 2006b. Predicting pathogen introduction: West Nile virus spread to Galapagos. *Conserv. Biol.* **20:** 1224–1231.
67. Kilpatrick, A.M., P. Daszak, M.J. Jones, *et al*. 2006c. Host heterogeneity dominates West Nile virus transmission. *Proc. R. Soc. B: Biol. Sci.* **273:** 2327–2333.
68. Kilpatrick, A.M., P. Daszak, L. Kramer, *et al*. 2006d. Predicting the transmission of West Nile virus. *Am. J. Trop. Med. Hyg.* **75:** 139–139.
69. Hubalek, Z. 2003. Emerging human infectious diseases: anthroponoses, zoonoses, and sapronoses. *Emerg. Infect. Dis.* **9:** 403–404.
70. Office of Technology Assessment. U.S. Congress (OTA). 1993. *Harmful Non-Indigenous Species in the United States. OTA Publication OTA-F-565*. US Government Printing Office, Washington, DC.
71. Perrings, C. 2007. Pests, pathogens and poverty: biological invasions and agricultural dependence. In *Biodiversity Economics: Principles, Methods and Applications*. A. Kontoleon, U. Pascual & T. Swanson, Eds.: 133–165. Cambridge University Press. Cambridge.
72. Leung, B., D.M. Lodge, D. Finnoff, *et al*. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proc. R. Soc. London, Biol. Sci.* **269:** 2407–2413.
73. Keller, R.P., D.M. Lodge, M.A. Lewis & J.F. Shogren, Eds. 2009. *Bioeconomics of Invasive Species: Integrating Ecology, Economics, Policy and Management.* Oxford University Press. Oxford.
74. Keller, R. & D.M. Lodge. 2010. Prevention: designing and implementing national policy and management programs to reduce the risks from invasive species. In *Bioinvasions and Globalization: Ecology, Economics, Management and Policy*. C. Perrings, H. Mooney & M. Williamson, Eds.: 220–234. Oxford University Press. Oxford.
75. Tatem, A.J., S.I. Hay & D.J. Rogers. 2006. Global traffic and disease vector dispersal. *Proc. Natl. Acad. Sci.* **103:** 6242–6247.
76. Ruiz, G.M. & J.T. Carlton. 2003. Invasion vectors: a conceptual framework for management. In *Invasive Species: Vectors and Management Strategies*. G.M. Ruiz & J.T. Carlton, Eds.: 461–462. Island Press. Washington, DC.
77. Burgiel, S., G. Foote, M. Orellana & A. Perrault. 2006. *Invasive Alien Species and Trade: Integrating Prevention Measures and International Trade Rules*. Center for

International Environmental Law, Defenders of Wildlife and TNC. Washingon, DC.

78. Perrault, A., M. Bennett, S. Burgiel, *et al*. 2003. *Invasive Species, Agriculture and Trade: Case Studies from the NAFTA Context*. North American Commission for Environmental Cooperation. Montreal.
79. Pyšek P., V. Jarošík, J. Pergl, *et al*. 2009. The global invasion success of Central European plants is related to distribution characteristics in their native range and species traits. *Divers. Distrib.* **15:** 891–903
80. Convention on Biological Diversity. 2008. *In-depth Review of Ongoing Work on Alien Species that Threaten Ecosystems, Habitats or Species: Addendum – Preliminary Report of Expert Workshop on Best Practices for Pre-import Screening of Live Animals in International Trade* (9–11 April 2008, South Bend, Indiana, USA) UNEP/CBD/COP/9/INF/31/Add.1 (5 May 2008).
81. World Health Organization. 2005. *International Health Regulations*. WHO Press. Geneva.
82. World Trade Organization. 1995. *The Sanitary and Phytosanitary Agreement*. WTO. Geneva.
83. Perrings C., M. Williamson, E.B. Barbier, *et al.* 2002. Biological invasion risks and the public good: an economic perspective. *Conserv. Ecol.* **6:** 1. [online] URL: http://www.consecol.org/vol6/iss1/art1
84. Schiff, M. & L.A. Winters. 2003. *Regional Integration and Development*. World Bank, Washington, DC.
85. World Bank. 2005. *Global Economic Prospects.* World Bank, Washington, DC.
86. Thomas, M.H., & A. Randall. 2000. Intentional introductions of nonindigenous species: a principal-agent model and protocol for revocable decisions. *Ecol. Econ.* **34:** 333–345.
87. Lovell S.J. & S. Stone. 2005. The economic impacts of aquatic invasive species: a review of the literature. Working Paper # 05–02, U.S. Environmental Protection Agency National Center for Environmental Economics, Washington, DC.

