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Invasive species: a costly catastrophe for native biodiversity

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Abstract

Species introduced from outside their natural range can be an economic boon, because they often seem to do better in their new home than in their place of origin. For example, various species of eucalyptus from Australia are widespread in Southeast Asia, China, India, California, and various parts of Africa, and South Africa's colourful proteas bless many of the world's gardens. Further, 'natural' is becoming an increasingly obsolete concept, as virtually all ecosystems have a strong and increasing anthropogenic component. People are designing the kinds of ecosystems they find congenial. The great increase in the introduction of aliens that people are importing primarily for aesthetic reasons — ornamentals to make their gardens more attractive — often leads to a net increase in species richness in their destination. It is quite likely, for example, that many parts of the world have far more species now than ever before, though this great increase of species numbers is usually at least partly at the expense of indigenous species (and thus reduces global species diversity). But a species introduced for noble economic or aesthetic objectives may escape into the wild, invading native ecosystems with disastrous results: they become alien invasive species (AIS). Greatly improved transport that enables traders to move goods around the world quickly is providing ideal opportunities for the accidental introduction of AIS, ranging from zebra mussels to disease-carrying mosquitoes to bacteria and viruses. It appears that few purposeful introductions have been accompanied by a careful consideration of the full costs involved. When the costs have become apparent, they can be astronomical; one study in the United States estimates that costs associated with alien species amount to some US$136 billion per year, and the recent disastrous fires in South Africa appear to be at least partly due to the spread of AIS. These costs usually must be paid by someone other than those who sponsored or promoted the introduction — often the general public. Decision-makers need to invest more in assessing the potential impacts before allowing introductions and to incorporate more biosecurity measures once the species has been introduced. Accidental introductions by definition are not exposed to a prior cost-benefit assessment, but assessments of the costs of such introductions can justify increased budgets to control and limit such accidental introductions. AIS issues also link to other issues of major policy concern, such as biotechnology, global trade, water, human health, and climate change. The Convention on Biological Diversity offers an important opportunity for addressing the complex global problems of introduced species through improved international cooperation.

Introduction

Many of us may see the problem of alien invasive species (AIS) as primarily a management challenge, and indeed this meeting will be addressing this part of the problem in some detail. In setting the stage for this very practical discussion, I will focus on several policy issues. Because the issue of AIS has ramifications throughout modern economies, involving such issues as global trade, agriculture, economics, health, water management, climate change, and genetic engineering, it goes to the heart of the problems most politicians are spending much time debating, usually without reference to AIS. The intention of this paper is to suggest some of the ramifications of alien invasive species through many other areas of human endeavour. In other words, we are not talking about a highly specialised field, but rather about a symptom of much more fundamental challenges in the way that modern society is attempting to adapt to changing conditions.

For example, many people warmly welcome globalisation of trade, and growing incomes in many parts of the world are leading to increased demand for imported products. North American nursery catalogues, for example, offer nearly 60 000 plant species and varieties to a global market, often through the Internet (Ewel *et al.*, 1999). A generally unrecognised side effect of this globalisation is the introduction of exotic or alien species; at least some of which may be harmful. Governments have expressed their concerns about this problem through the Convention on Biological Diversity (CBD), which calls on the Parties to "prevent the introduction of, control or eradicate those alien species, which threaten ecosystems, habitats, or species" (Article 8h). Its Conference of Parties will be considering guiding principles for dealing with AIS at its meeting in Nairobi this May.

This paper will examine the history and ecology of the global trade in species of plants and animals, briefly explore some impacts of AIS, compare purposeful and accidental introductions, suggest how climate change relates to the global economy and AIS, introduce some economic concepts relevant to the issue of global trade and alien species, explore the relationship between GMOs and AIS, and recommend steps that could be taken by the global community to deal more effectively with the issue of harmful alien species.

Species are introduced into new habitats by people for three general reasons: (i) accidental introductions (often invertebrates and pathogens); (ii) species imported for a limited purpose which then escape; and (iii) deliberate introductions (usually plants and vertebrates) (Levin, 1989). Many of the deliberate introductions relate to the human interest in nurturing species that are helpful to people. This is particularly true of agricultural, forestry, and ornamental species. Indeed, in most parts of the world, the great bulk of human dietary needs are met by species that have been introduced from elsewhere (Hoyt, 1992); it is difficult to imagine an Africa without cattle, goats, maize, and cassava — all introduced species. Species introductions in this sense, therefore, are an essential part of human welfare in virtually all parts of the world. Further, maintaining the health of these introduced species of undoubted net benefit to humans may require the introduction of additional species for use in biological control programmes which import natural enemies of, for example, agricultural pests (Waage, 1991; Thomas and Willis, 1998).

Many other AIS are due to unintentional 'hitchhiking' through international trade, with invaders stowing away in ships, planes, trucks, shipping containers, and packing materials, or arriving on nursery stock, unprocessed logs, fruits, seeds, and vegetables (OTA, 1993). People have always been on the move, carrying other species with them. Australian aborigines brought in the dingo, Polynesians sailed with pigs, taro, yams, and at least 30 other species of plants (and rats and lizards as stowaways), and the Asians who first peopled the Americas also brought dogs with them. The impact of these earliest colonists was devastating on the local species, leading to numerous extinctions (see, for example, Martin and Klein, 1984) and numerous introductions, at least by the later colonists who already had developed agriculture (Cuddihy and Stone, 1990). The spread of cattle through much of Africa over the past few thousand years also brought in other associated new species (including rinderpest in 1889, which reached the Cape just ten years later), as well as cultural practices. The period of European colonialism which began with the development of more effective global transport and military technology (Crosby, 1972; Keegan, 1993) ushered in a new era of species introductions, as the Europeans sought to recreate the familiar conditions of home (Crosby, 1986). They took with them species such as wheat, barley, rye, cattle, pigs, horses, sheep, and goats, but in the early years their impacts were limited by the available means of transport. Once steam-powered ships came into common use, the floodgates opened and over 50 million Europeans emigrated to distant shores between 1820 and 1930, taking numerous plants and animals with them and often overwhelming the native flora and fauna.

As a biodiversity issue it is not always possible to identify invasions as inherently 'bad'; di Castri (1989) asserts that overall, the central European flora has undergone an enrichment of diversity over historical time as a result of human-induced plant invasions. And the saline Lake Nakuru was transformed from an ecosystem of very low diversity (a large population of flamingos, two species of algae and a few invertebrate species) to one of much higher diversity (including 30 species of fish-eating birds) after the introduction of a fish, *Tilapia grahami*, to control mosquitoes in 1961 (Jacobs, 1975). More generally, cities — where the majority of the world's people are living at the turn of the century — are greatly enriched by invasive species of plants. Many invasive species seem to do best in urban and urban-fringe environments where long histories of human disturbance have created vacant niches and abundant bare ground. Cities also tend to be the focal points of the global economy and the entry points for many invasives. Thus London has some 2100 species of flowering plants and ferns growing wild while the rest of Britain has no more than 1500 species, and Berlin has 839 native species of plants and 593 invasives (Kowarik, 1990; McNeely, 1995).

Global trade has greatly increased in recent decades: the growth in global economic output during the 1980s was greater than that during the several thousand years from the beginning of civilisation until 1950 and the 1990s were even more prolific. The value of total imports increased from about US$192 billion in 1965 to $4.8 trillion in 1995, a 25-fold increase in 30 years. Imports of agricultural products and industrial raw materials — those which have the greatest potential to contribute to the problem of AIS — amounted to $850 billion in 1998, up from $55 billion in 1965. This tremendous economic performance has been built on an increasingly homogenised foundation of information, finance, culture, and ecosystems.

This homogenisation — which has been termed 'biological pollution' (Luken and Thieret, 1996) — reduces the diversity of crops and livestock and can increase their vulnerability to both native and exotic pests, often leading to the increased use of pesticides which may have broad negative impacts on ecosystems. Thus introductions may lead to 'cascades' of effects that were not part of the original decisions that led to the introduction. Species introductions may thus be considered part of the class of phenomena that economists call 'externalities', impacts of an activity that affect others outside the activity; the interests of those others are usually ignored by those undertaking the activity (see below).

Some protected areas established to conserve native species have been profoundly affected by introduced species (Bratton, 1982), and on some islands introduced species closely match or even outnumber native ones (Table 1). If one judges biodiversity only by species richness, then those islands are now twice as valuable as they were when they were 'natural'. However, most known extinctions — at least of birds — have taken place on islands, so while the individual islands may have more species, the world as a

Table 1 Known numbers of invasive and native species in various countries/areas

Country/Area	*Number of native species*	*Number of invasive species*	*Source*
New Zealand (plants)	1,790	1,570	Heywood, 1989
Hawaii (plants)	956	861	Wagner *et al.*, 1990
Hawaii (all species)	17,591	4465	Miller and Eldridge, 1996
Tristan de Cunha (plants)	70	97	Moore, 1983
Campbell Island (plants)	128	81	Moore, 1983
South Georgia (plants)	26	54	Moore, 1983
Southern Africa (FW fish)	176	52	De Moor & Bruton, 1988; Bruton & Van As, 1986
California (FW fish)	83	50	Moyle, 1976
USA (plants)	22,000	5,000	Pimentel *et al.*, 2000

whole has lost diversity. The unique has been replaced by the commonplace. Thus, despite some arguably positive effects on biodiversity at the local level, overwhelming evidence indicates the profoundly negative effects of introductions on species and genetic diversity at both the local and global level. Such introductions can lead to severe disruption of ecological communities (Drake, 1989; Smith, 1972; Zaret and Paine, 1973; Mooney and Drake, 1986; Carlton and Geller, 1993), and heavily influence the genetic diversity of indigenous species.

In the cases where the direct cause of species extinction is identifiable, introduced species head the list. For example, introduced mammals are responsible for all but one of the nine known extinctions of endemic vertebrate species or sub-species from the islands of north-west Mexico, and virtually all of the avian extinctions on Pacific islands have been due to invasive mammals (including *Homo sapiens*). Globally, almost 20% of the vertebrates thought to be in danger of extinction are threatened in some way by invasive species (Table 2). The single biggest vertebrate extinction event in recent history is the probable loss of at least 200 of the 300 endemic cichlid species of fish in Lake Victoria as a result of the introduction of the Nile perch, *Lates niloticus*, to the lake (Lowe-McConnell, 1993); this was exacerbated by eutrophication of the lake and the introduction of new fishing gear. The global effects of certain invasive species such as the European pig *Sus scrofa*

Table 2 The percentage of threatened terrestrial vertebrate species affected by introductions in the continental landmasses of the different biogeographic realms and on the world's islands. (The total number of threatened species in the realm is given in brackets).

Taxonomic group	*Mainland areas* %	(n)	*Insular areas* %	(n)
Mammals	19.4	(283)	11.5	(61)
Birds	5.2	(250)	38.2	(144)
Reptiles	15.5	(84)	32.9	(76)
Amphibians	3.3	(30)	30.8	(13)
Total for all groups considered	12.7	(647)	31.0	(294)

Source: Macdonald *et al.*, 1989

(Oliver, 1994), rats *Rattus* spp. (Atkinson, 1985; Brockie *et al.*, 1989; Stuart and Collar, 1988) and the aquatic plants *Salvinia molesta* and *Eichhornia crassipes* (Ashton and Mitchell, 1989) also attest to the destructive power of invasives.

The general global picture is, then, one of tremendous mixing of species with unpredictable long-term results. While many introduced species have special cultivation requirements which restrict their spread, many other species are finding appropriate conditions in their new homes while many more may invade their new habitats and constantly extend their distribution, thereby representing a potential threat to local species. The future is certain to bring considerable additional ecological shuffling as people influence ecosystems in various ways, not least through both purposeful and accidental introduction of species. This shuffling will have both winners and losers although the overall effect will likely be a global loss of biodiversity at species and genetic levels.

Global trade and species introductions: intentions and accidents

The trade-based global economy stimulates the spread of economically-important species, often with funding from development agencies to establish plantations of pines, rubber, oil palm, pineapples, and coffee, and fields of soybeans, cassava, maize, sugar-cane, wheat, and other species in countries far from their place of origin. But it also stimulates the accidental spread of species through a variety of pathways. While it is difficult with present information to determine precisely how much of the invasives problem globally is due to conscious intent and how much to inadvertence, some hints are available:

- OTA (1993), in a comprehensive review, concluded that about 4500 exotic species occur in a free-ranging condition in the United States, and that about 20% of them have caused serious economic or ecological harm. More recent studies claim far higher rates, up to 50 000 introduced species in total, including 5000 non-native plant species now established in the wild, amounting to 23% of the total flora (Pimentel *et al.*, 2000).

- OTA (1993) found that raw logs from Siberia imported to the West Coast of the US carried with them pests with significant potential negative economic impacts. These included the Siberian gypsy moth, which is considered more damaging to coniferous forests than the European gypsy moth and which has already caused significant damage. (As a result, imports of raw logs from Siberia were banned).

- With an estimated 3000 species, on any one day, of freshwater, brackish water (estuarine) and marine protists, animals, and plants in motion around the world in the ballast of ocean-going ships, numerous opportunities are available for the invasion of aquatic environments by exotic organisms. Examples from the last decade include: the Japanese sea star *Astrias amurensis* has appeared in Australia, where it has broad potential impacts on the shell fish industry; the Japanese shore crab *Hemigrapsus sanguineus* has colonised Atlantic North America (where it is now becoming relatively common from Cape Cod to Chesapeake Bay); the American comb jelly fish *Mnemiopsis leidyi* has invaded the Black and Azov Seas and has been linked to the near-demise of regional anchovy fisheries; the Chinese estuarine clam *Potamocorbula amurensis* has become one of the most abundant benthic organisms in San Francisco Bay, where the disappearance of spring phytoplankton blooms in parts of the Bay and extensive decreases in zooplankton have been attributed to high densities of this clam; and the Indo-Pacific mussel *Perna perna* has colonised Caribbean mangrove ecosystems and Gulf of Mexico jetties, where it forms extensive monoculture-like beds. In the Great Lakes of Canada and the US, three European fish, two species of zebra mussels, and a carnivorous water flea, all unknown from North America in 1980, are now six of the most common species regionally or in large parts of those waters.

It appears, then, that 'the problem of invasive species' has two very distinct elements: species that are introduced consciously, and for which management procedures such as environmental impact assessments are available; and inadvertent invasives, which may be far more pervasive and far less amenable to management intervention. I will return to this point later, but I would first like to digress slightly into another externality: climate change.

Globalisation, climate change and exotic species

The Intergovernmental Panel on Climate Change (IPCC, 1996) has concluded, on the basis of long and detailed studies, that human activities are having a discernible impact on the climate, primarily through the burning of fossil fuels which is increasing the amount of carbon dioxide in the air and thereby contributing to the so-called 'greenhouse effect'. Much of the global economy is based on these fossil fuels: global trade in fossil fuels was \$335 255 000 000 in 1990 (WRI, 1994). Without the cheap petroleum-based transport, which subsidises global trade, commodities would be far more expensive and trade would be greatly reduced, with a commensurate reduction in the threats from introduced species.

Climate change could open up new opportunities for introduced species that could devastate native flora and fauna. For example, if the species, which are dominant in the native vegetation, are no longer adapted to the environmental conditions of their habitat, what species will replace them? It may well be that AIS will find these 'new' habitats especially attractive, and the increasing presence of new species and the decline of old ones will drastically change successional patterns, ecosystem function, and the distribution of resources. Thus concepts of global change need to include consideration of the behaviour and distribution of invasive species. It seems highly likely that invasive species are going to have even more opportunities in the changed future climate than they have at present.

Many variables may limit the distribution of a species in different parts of its range, and detailed studies are required to define the distribution limit of various invasive species as climate change. Sutherst *et al.* (1996), for example, used a computer programme for comparing the relative climatic potential for population and persistence of the invasive Cane toad (*Bufo marinus*) in relation to season and locality. This type of study is likely to be increasingly relevant and important.

Costs and benefits of alien species

It is probably fair to say that most people who seek to introduce a non-native species into a new habitat are doing so for an economic reason. They may wish to increase their profits from agriculture, they may believe that the public will like a new flower from a distant part of the globe, or they may think that non-native species will be able to carry out functions that native species cannot carry out as effectively (examples of these will be given below).

But it may also be fair to say that most of those introducing exotic species have not carried out a thorough cost-benefit analysis before initiating the introduction, at least partly because they may not have been aware of the advantages of such analyses. On the other hand, it is also possible that at least some people would prefer to ignore ('externalise') the negative impacts that may follow from species introductions, because they might be expected to compensate those who are negatively affected.

Similarly, those who have been responsible for inadvertently introducing species into new habitats may not have been willing to make the investment necessary to prevent such accidents from occurring. They may not have realised the dangers, and in any case the dangers would be unlikely to have much economic impact on their own welfare. Rather, the costs of such accidents are borne by people other than those who are permitting the accidents to happen. Thus the costs of introducing alien species into new habitats are 'externalised' in considerations of the costs of global trade. The line of responsibility is insufficiently clear to bring about the necessary changes in behaviour, so the general public — or future generations — ends up paying most of the costs. Ewel *et al.* (1999) call for research to identify conflicting interests regarding benefits and risks of introductions, to substantiate purported evaluations of those benefits and risks, and to determine the likely distribution of benefits and risks among sectors of society.

This paper will introduce, in a preliminary way, some of the economic factors affecting the issue of alien species. It will quickly become clear that this field is still relatively immature, but that considerable benefits for biodiversity will come from a more inclusive consideration of economic factors, and the application of economic tools to deal with them.

Good intentions: somebody is going to make money

Many non-native species have been introduced for economic purposes. Introduced fish can produce excellent sport fishing, introduced plants can provide food, fodder, timber, and energy, and introduced insects can provide biological controls. A few examples (from among hundreds that could be quoted):

- Brush-tailed possums from Australia were introduced to New Zealand between 1858 and 1900 to establish a fur trade, but in New Zealand they have fewer competitors, fewer predators, and fewer parasites than in their native Australia, so they have successfully spread and have sometimes reached densities ten times greater than in their native Australia. They have been a bonanza for the fur industry.

- A number of woody plants from various parts of the world, such as acacias from Australia, were introduced into South Africa in the middle of the 19th century for purposes of dune stabilisation, tannin extraction, and firewood. This appears to have been an economically successful invasion, with the greater Cape Town region alone supporting a 30 million Rand charcoal and firewood industry.

- The Triclad flatworm *Platydemus manokwari*, first described from New Guinea in 1963, is a successful predator of the giant African snail *Achatina fulica*, so it was transported as a biological control agent to areas where the African snail had become established in the Pacific.

- Water hyacinth *Eichhornia crassipes* was introduced into China from South America in the 1930s and was spread through mass campaigns in the 1950s to the 1970s as an ornamental plant, to provide livestock food, and to control pollution through absorbing heavy metals.

But something went wrong: somebody had to pay the costs

But we all know that there is no free lunch. Introduced species can carry a heavy price-tag in terms of reduced crop and livestock production, loss of native biodiversity, increased production costs, and so forth. For example, Pimentel *et al.* (2000) estimate that the total costs to the US of invasive species is $136 billion per year (Table 3).

All of the introductions listed above carried with them some hidden — or, in retrospect, obvious — costs:

- The Australian brush-tailed possums introduced into New Zealand have caused considerable damage to native forests, changing forest composition and structure through the defoliation and progressive elimination of favoured food plants. Note that none of these costs are particularly relevant to those interested primarily in the benefits from furs.

Table 3 Estimated annual costs associated with alien invasive species in the USA

Type of organism	*Total costs (x US$1 million)*
Plants	24,059.5
Mammals	37,105.5
Birds	1,900
Reptiles and amphibians	5.6
Fishes	1,000
Anthropods	20,055
Molluscs	1,305
Microbes	41,200
Total	136,630

Source: Pimentel *et al*., 2000. Only some species are covered.

- As a result of the introduced species, South Africa's highly-endemic Cape flora is under serious threat and the watersheds are becoming less productive, potentially causing a considerable increase in the price of water (Wilgen *et al.*, 1996). (See below for more details).

- The Triclad flatworm now poses a serious threat to the native gastropod fauna of the Pacific region. This is especially troubling because the Pacific has seen a remarkable radiation of the snail family Partulidae, and some 24 of these are on the 1994 IUCN Red List of Threatened Animals. The Triclad flatworm has become established on Guam, Saipan, Tinian, Rotar, and Palau.

- In China, the water hyacinth has become the worst weed in many aquatic habitats, leading the loss of species of both plants and animals. In Dianchi Lake, just outside of Kunming, Yunnan, the total number of fish species has declined from 68 to about 30 and Chinese scientists attribute this to water hyacinth. Reduction of the lake area as a result of the water hyacinth infestation has also caused notable climatic changes in Kunming (Jianqing *et al.*, 1995).

Few of these examples have explicit costs attached to them, but qualitative costs are often available. For example, in the early 1900s, the most economically important hardwood species in eastern American forests was the chestnut (*Castanea dentata*), but the chestnut blight brought in on diseased horticultural stock from China killed nearly a billion trees and all but eliminated this species, leading to profound ecosystem changes in the eastern hardwood forests (USDA, 1991).

Despite such figures, the issue of costs and benefits is not always clear, at least partly because different people have different perceptions of what these are. Luken and Thieret (1996), for example, report that within less than a century after its deliberate introduction into North America to improve habitat for birds, serve ornamental functions in landscape plantings, and stabilize and reclaim soil, the Amur honeysuckle had become established in at least 24 states in the eastern USA. While many resource managers perceive the plant as an undesirable element, gardeners and horticulturists consider it an extremely useful plant. Thus the 'noxious invasive' of one group is the 'desirable addition' of other groups. How can costs and benefits be determined in such a case?

Diamond *et al.* (1991) have estimated the costs and benefits of controlling the invasive tree *Melaleuca quinquenervia* in Florida. Total annual benefits, based largely on tourism, of preventing infestation from the tree would be $168.6 million, while the costs to honey producers to whom the tree provides nectar would amount to just $15 million. Again, the costs and benefits in this case are differentially distributed: those who suffer losses are unlikely to be compensated, while those who benefit pay few of the costs.

Considerable work has now been done in the USA, at least, on the cost-benefit ratios for various forms of managing invasive species (though the distribution of these continue to be ignored). OTA (1993) presents a summary of these, with Table 4 highlighting a number of cases. Note the very wide range of cost-benefit ratios, though in nearly all cases the benefits of control far outweigh the costs involved. This strongly suggests that significantly increased investments in managing invasive species is justified in economic terms, though again those paying the costs — usually the taxpaying public — may not always be the primary beneficiaries; and those who earned the benefits from the invasives in the first place are paying a tiny proportion of the costs.

As an indication of one interesting approach measuring costs and benefits, Wilgen *et al.* (1996) presented a case study showing how invasion by alien plants has affected water resources in the mountain catchment areas of the Western Cape Province, South Africa. They found that the sustained supply of high-quality water depends on maintaining the cover of fynbos (shrubland) vegetation. The fynbos binds the soil, preventing erosion, while its relatively low biomass ensures conservative water use and low-intensity fires, which in turn ensure high water yields and low impacts on the soil from periodic fires. Fynbos-clad mountain catchments fulfil approximately two-thirds of the Western Cape's water requirements, an ecosystem service that plays a crucial role in the region's economy and contributed to a gross domestic product of US$15.3 billion in 1992. The fynbos flora is widely harvested for cut flowers, dried flowers, and thatching grass, producing a combined value in 1993 of $18–19.5 million and providing a livelihood for 20–30,000 people.

However, catchment management is complicated by the invasion of the fynbos vegetation by non-indigenous woody trees and shrubs, which increase biomass and reduce runoff. Fynbos ecosystems are remarkably prone to invasion by alien woody species, which displace the native fynbos and increase biomass by between 50% and 1000%. These invasive plants were introduced to South Africa to provide a source of fast-growing timber in the relatively treeless landscape, as hedge plants, as agents for binding the shifting dunes along the coast, and as ornamental plants. The most important invasive species originated in Australia and the Mediterranean-climate areas of Europe and North America. On the slopes of Table Mountain, above Cape Town, invasion by alien species has increased fire intensities, leading to severe soil erosion.

A computerised model indicated that alien plants would invade approximately 40% of the area within 50 years and 80% after 100 years, with a corresponding increase in biomass of 150% or more. This invasion would result in an average decrease of 347 cubic metres per ha per year of water at the end of 100 years, resulting in average losses of more than 30% of the water supply to the city of Cape Town. In some years, when large areas would be covered by mature trees, losses would be much greater, exceeding 50% of the runoff from similar uninvaded areas. They concluded that investments in managing alien plants at a level that would ensure that they are no longer part of the ecosystem would lead to a net unit cost of water of $12 per cubic metre, as compared to $14 without the management of alien plants. Happily, this reasoning has carried the day, and the control of AIS on the Cape in the name of water conservation has been an outstanding success story.

One final point: the problems of alien invasive species are so serious that actions must be taken even before we can be 'certain' of all of their effects. After all, it is much easier to disprove a hypothesis than it is to prove one. In any case, mechanical removal, biocontrol, chemical control, shooting, or any other approach to controlling alien invasive species needs to be carefully considered prior to use to ensure that the implications have been fully and carefully considered, including impacts on human health, other species, and so forth. A public information programme is also needed to ensure that the proposed measures are likely to be effective as well as socially and politically acceptable.

While it is important to identify costs and benefits, such determination does not automatically determine a decision because value judgements and distributional questions are nearly always involved. Further, the magnitude of the costs may sometimes be so high as to render an action politically unacceptable, even when the benefits are likely to be even greater; part of the problem is that the benefits may be

Table 4 Cost-benefit ratios for dealing with AIS in the USA (based on OTA, 1993) (Dollar figures in millions)

AIS	*Benefits of control/ prevention/eradication*	*Costs*	*Ratio*
Melaleuca	183	16	11.4/1
Water hyacinth	3.8	.28	13.6/1
Sea lamprey	296	9.8	30/1
Alfalfa blotch leafminer	17	2	8.5/1
Purple loosestrife	53	2	26.5/1
Mediterranean fruitfly	1,829	93	19.6/1
Foot and mouth disease	25,275	1,013	25/1
Siberian log imports	64,704	39	1659/1

widely spread throughout the public over a period of many years, while the costs of control may need to be paid rather quickly by tax payers.

Global solutions to the global problem of alien species

Links with the World Trade Organization

While this paper has supported the argument that global trade promotes invasive species, it is possible that agreements under the World Trade Organization could offer some help in dealing with exotic species, though bans and restrictions should be founded on science-based risks so that they will be less likely to be challenged before the WTO. But such risk assessment is often extremely expensive; for example, the risk assessment for the proposed import of raw Siberian larch cost the US Government about $500,000 (Jenkins, 1996).

As Yu (1996) points out, the GATT Treaty contains three important provisions to protect the environment and human health and these might be expanded to deal with exotic species. These provisions include the Agreement on Sanitary and Phyto-sanitary Measures, the Agreement on Technical Barriers to Trade, and Article 20: General Exceptions, which protects the right of members to take any measures “necessary to protect human, animal, or plant life or health”.

Even so, the impact of trade on biodiversity in general and AIS in particular remains poorly addressed. Free traders maintain that liberalised markets will solve environmental problems by promoting more efficient use of natural resources, while others maintain that global markets actually undermine efforts to protect the environment. The former argue that increased revenues will lead to decreased environmental damage, while the latter contend that increasing revenues are precisely the problem that leads to over-consumption of biological resources. UNCED was relatively ineffective in addressing trade issues, much less trade’s promotion of invasives. It endorsed the establishment of strong environmental rules on trade without exploring the basic principles of trade reform that would enable a balance to be struck between trade and environment. The language adopted by Agenda 21 in Rio generally adopted the line being promoted by the GATT Uruguay round of negotiations but ignored the possibility that GATT could itself undermine the environmental measures initiated by the Earth Summit (Prudencio, 1993).

Links with the CBD Biosafety Protocol

Non-native species include genetically modified versions of native organisms (Ewel *et al.*, 1999). Some scientists believe that these genetically modified organisms (GMOs) offer a new and more serious threat to biodiversity than do non-modified species. The crux of the issue is whether the GMOs are likely to be more competitive, or less competitive, than native species. After all, non-modified introduced species contain millions of genes, while most GMOs have only a few of their genes modified. Further, the genetic modification is designed for specific results desired by humans, such as pest resistance or herbicide resistance; and these may not necessarily provide for better survival in the rigours of a competitive world. Based on these and many other considerations, governments have been discussing for five years what to include in a Biosafety Protocol.

In Montreal governments agreed at the end of January 2000 to a legally binding protocol for protecting the environment from risks posed by the transboundary transport of one type of alien species, namely living modified organisms (LMOs) created by modern biotechnology. The Cartagena Protocol on Biosafety will enable governments to indicate whether they are willing to accept imports of agricultural commodities that include LMOs by communicating their decision to the world community via an Internet-based Biosafety Clearinghouse. Shipments of such commodities that may contain LMOs are to be clearly labelled. More strict Advanced Informed Agreement (AIA) procedures will apply to seeds, live fish, and other LMOs that are to be intentionally introduced into the environment (and therefore might be in danger of becoming invasive). In these cases, the importer must provide detailed information to each importing country in advance of the first shipment and the importer must then authorise the shipment. The intention is to ensure that recipient countries have both the opportunity and the capacity to assess risks involving the products of modern biotechnology.

The Protocol clearly is part of the global trade regime and is to be mutually supportive of any agreements under the World Trade Organisation (WTO). This might be a challenge, because the Protocol is based on the precautionary principle (which states that potentially dangerous activities can be restricted or prohibited even before they can be scientifically proven to cause serious damage), whereas decisions under trade law typically require ‘sufficient scientific evidence’ to lead to such restrictions. LMOs include food crops, fish, or trees that have been genetically modified for greater productivity, resistance to pests or diseases, or other valued characteristics. Seeds and fish are particularly important because they are used intentionally to propagate or reproduce LMOs in the environment. These LMOs form the basis for a multi-billion dollar global industry. Pharmaceuticals derived from LMOs form the basis of an even larger industry, but are not covered by this agreement. The Protocol opens the door to greater cooperation between those exporting LMOs and the importing countries who may need technical, financial, institutional, and human resources to assess and manage risks, establish adequate information systems, and develop expert human resources in biotechnology.

The implications of all this for the issue of AIS is that many of the principles in the Biosafety Protocol could be adapted as part of a broader Biosecurity Protocol that deals more comprehensively with biological threats to human welfare.

Other global approaches

As suggested above, other international conventions might also be brought to bear on the invasive species problem. Particularly interesting in this regard is the Climate Change Convention, which has very broad government support, especially in the industrialised countries. It also has an associated scientific body, the Inter-governmental Panel on Climate Change; the latter has not yet had the issue of invasive species brought to its attention, but is increasingly recognising the importance of climate change on biodiversity more generally. It too could be mobilised in support of a global effort to address the invasive species problem.

Another global solution might be through the World

Health Organisation, especially for invasives which are relevant to human health — primarily viruses and bacteria. While most presentations at this meeting are looking at insects, vertebrates, and plants, the bacteria and viruses may be much more interesting to governments and the general public, as indicated by the popularity of books and films dealing with the Ebola virus. Invasive species first got the attention of policy makers in relation to introduced pathogens inadvertently spread by humans, and the spread of disease organisms must be considered as part of the discussion of AIS. Mechanisms designed to address these disease-causing invasives may also be relevant to other parts of the invasive species problem.

Conclusions and Recommendations

One of the main intentions of liberalising trade as advocated by the World Trade Organisation is to stimulate an even greater volume in materials traded, thereby offering — in addition to more goods for consumers — greater opportunities for introduction of non-native species and ultimately greater homogenisation of ecosystems. Despite the evidence of significant impact, the response of governments is inadequate to prevent the increased trade that it is promoting from resulting in more introductions of harmful species (Jenkins, 1996). And if even governments with relatively well developed control structures are unable to deal with the problem, what of the many tropical countries that have even less capacity for dealing with such problems? Here are some suggestions to the global community:

- Presume that intentional introductions are a threat to ecosystems, habitats, or species until proven otherwise. Proposers of intentional introductions should be expected to conduct an environmental impact assessment and examine alternatives such as use of native species.

- Use the Convention on Biological Diversity more effectively. As this paper, and many others at this conference, has indicated, the issue of invasive species is clearly also an issue of biosafety. Yet the Convention's Biosafety Protocol addresses only living modified organisms (Article 19.3), which more properly are just a subset of the invasive species problem covered by Article 8(h). Perhaps it is timely now to address the broader issue of Biosecurity under the CBD. Biosecurity can be defined as "managing the risks posed by organisms to the economy, environment, and human health through exclusion, eradication and control". It therefore is a concept that includes biosafety but takes a far more inclusive approach.

- At a very minimum, all those involved in agricultural quarantine or food inspection should be made aware of the provisions of the CBD and its Biosafety Protocol, and the implications of these provisions for their work. While risk assessment and testing procedures may be acceptable from an agricultural perspective, they may be fundamentally flawed from the ecological perspective advocated under the CBD.

- Bring the issue of invasive species to the attention of the World Trade Organisation, perhaps through a strong statement adopted by the Conference of the Parties of the Convention on Biological Diversity. Such a statement will need to be relatively concise and explicit, and contain within it specific responses that would be expected from the WTO.

- Build on the experience of countries faced with significant invasive species problems (e.g. USA, South Africa, Australia, New Zealand) to develop further a body of principles and practice that could be transferred to developing countries.

It is apparent from the material presented in this paper, which is only a small sample of a much larger literature, that economics has much to contribute to programmes to address the problems of alien species. Decision-makers often find arguments couched in economic terms to be more convincing than those cast in emotive or ethical terms, and this paper has suggested some ways that economics-based arguments can be used to support stronger programmes to deal with invasive species. Without trying to be comprehensive, I suggest that at least the following actions be considered:

- Build an economics component into any international programme to deal with AIS. A partnership between ecologists working on invasive species and economists could be extremely productive. As South Africa has discovered, economic analysis can provide a useful and rigorous structure to guide policy makers who might otherwise 'externalise' some of the most relevant factors. Applying numbers to the problem can highlight the areas of debate and uncertainty, particularly when they look at the distribution of costs and benefits.

- In each country, or as part of each programme to deal with one or more invasive species, seek to quantify the costs and benefits involved. Ensure that such quantification is as complete as possible, so that no costs (or benefits) are 'externalised'. The ability of economists to provide useful analyses will depend to a large extent on how well biologists are able to estimate the probabilities of future impacts of alien species in a consistent, convincing, and comparable way. Because economic models provide little assistance where they rest on vague or equivocal predictions of biological events, an effective partnership between ecologists and economists is essential.

- Mobilise economic instruments, including such incentives as grants, taxes, and fines to ensure better compliance with programmes dealing with invasive species. Economic analysis can help design appropriate economic instruments, such as incentives and disincentives, helping to determine appropriate levels of fines and penalties for those introducing alien species.

The problem of human-induced invasive species is as old as our own species. But the severity of the problem has grown tremendously as the global economy has reached into virtually all corners of our planet. Invasive species problems present decision-makers with a moving target that will continue to move, perhaps even more quickly. Therefore, an 'adaptive management' approach is required, learning as we go along and modifying our management responses on the basis of experience. As a significant global problem with negative impacts on all countries, the problem of AIS is deserving of a significant global response.

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