The problems with invasive alien species, and implications for GMOs

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Abstract

Global trade has enabled modern societies to benefit from the unprecedented movement and establishment of species around the world. A new challenge is to identify when these alien or non-indigenous species are bringing about changes that have negative impacts on ecosystems, biodiversity, health, economics or other aspects of human welfare. This paper addresses two rather different aspects of this challenge: first, species that are intentionally moved to new locations to serve social or economic interests, but result in significant negative impacts; and second, species that are transported to new environments inadvertently and have significant negative effects on human welfare. Those alien species that become established in a new environment, then proliferate and spread in ways that damage human interests are considered "invasive alien species" (IAS) and are now recognized as one of the greatest biological threats to our planet's environmental and economic well-being. Numerous international instruments, have been developed to deal with certain aspects of the problem of IAS (eg. the Convention on Biological Diversity, the International Plant Protection Convention, etc.), of which over 40 instruments or programmes are already in force, and many more are awaiting finalisation and ratification. However, the threat of IAS is growing daily, and the economic and environmental impacts are severe, suggesting that these international instruments have been insufficient to prevent and combat IAS effectively. Every alien species needs to be treated for management purposes as if it is potentially invasive, unless and until convincing evidence indicates that it is harmless in the new range. This view calls for urgent action by a wide range of governmental, intergovernmental, private sector, and civil institutions. As with maintaining and enhancing health, education, and security, perpetual investments will be required to manage the challenge of IAS, especially if GMOs are considered as a potential sub-set of IAS.

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Riassunto
La globalizzazione ed il commercio internazionale hanno permesso alla società moderna di beneficiare del trasferimento e del successivo adattamento di specie diverse in tutto il mondo. Una nuova sfida è quella di valutare e stabilire quando queste specie aliene e non indigene possono subire cambiamenti che implichino un impatto negativo sull'ecosistema, sulla biodiversità, sulla salute, sull'economia e su altri aspetti legati al benessere dell'umanità. Questo articolo evidenzia due differenti aspetti di questa sfida: il primo riguarda le specie che vengono intenzionalmente spostate in altri ambienti per interessi sociali o economici e che hanno un impatto negativo; il secondo riguarda le specie che vengono trasportate inavvertitamente in nuovi ambienti e hanno effetti significantemente negativi sul benessere dell'uomo. Le specie aliene che si stabiliscono in un nuovo ambiente e poi proliferano e si espandono in un modo tale da danneggiare gli interessi umani vengono considerate "specie aliene invasive" (IAS) e sono considerate come una delle principali minacce al benessere economico e ambientale del nostro pianeta. Sono stati sviluppati numerosi strumenti, a livello internazionale, atti al trattamento di certi aspetti legati al problema delle IAS (come la Convenzione sulla Diversità Biologica, la convenzione Internazionale sulla Protezione delle Piante, etc.) e oltre 40 progetti o programmi sono attualmente in vigore mentre molti altri sono in via di finalizzazione o di ratifica. Nonostante ciò la minaccia dovuta a queste specie invasive aumenta ogni giorno e l'impatto economico e ambientale è serio, il che suggerisce che questi strumenti internazionali sono stati insufficienti a prevenire e combatterle efficacemente. Ogni specie aliena deve essere trattata come potenzialmente invasiva, fino a che non venga provata con certezza l'assenza di pericolosità per il nuovo ambiente. Questa visione richiede un'azione urgente da parte di una vasta gamma di istituzioni governative, intergovernative, private e civili. Per poter mantenere e migliorare la salute, l'educazione e la sicurezza saranno richiesti investimenti a lungo termine per gestire la sfida delle specie aliene invasive soprattutto se si considera che gli OGM sono consierati potenziali sottospecie delle IAS.

1. INTRODUCTION

Global trade has enabled modern societies to benefit from the unprecedented movement and establishment of species around the world. Agriculture, forestry, fisheries, the pet trade, the horticultural industry, and many industrial consumers of raw materials today depend on species that are native to distant parts of the world. The lives of people everywhere have been greatly enriched by their access to a greater share of the world's biological diversity. Expanding global trade is providing additional opportunities for further enrichment. But these movements of species by humans can also have negative impacts on local ecosystems and the species of which they are composed. Local and national economies are also being affected. A new challenge is to identify when these alien or non-indigenous species are bringing about changes that have negative impacts on ecosystems, biodiversity, health, economics or other aspects of human welfare.

This paper addresses two rather different aspects of this challenge: first, species -- often vertebrates or plants -- that are intentionally moved to new locations to serve social or economic interests, but result in significant negative impacts; and second, species that are transported to new environments inadvertently and have significant negative effects on human welfare.

Those alien species that become established in a new environment, then proliferate and spread in ways that damage human interests are considered "**invasive alien species**" (IAS). For example, a plant or animal transported beyond the ecosystem in which it occurs naturally may multiply out of control, endangering native species in the invaded ecosystem, undermining agriculture, threatening public health, or creating other unwanted - and often irreversible - disruptions. Preventing damage requires predicting which species can cause harm and preventing their introduction, and dealing effectively with the cases in which a species is already causing problems. It is not always simple to distinguish an alien species from an invasive one; taxa that are useful in one part of a landscape may invade other parts of the landscape where their presence is undesirable.

Invasive alien species are now recognized as one of the greatest biological threats to our planet's environmental and economic wellbeing. Most nations are already grappling with complex and costly invasive species problems. Examples include: zebra mussels (*Dreissena polymorpha*) affecting fisheries, mollusc diversity, and electric power generation in

Canada and the USA; water hyacinth (*Eichornia crassipes*) choking African waterways; rats exterminating native birds on Pacific islands; and deadly new disease organisms attacking human, animal, and plant populations in both temperate and tropical countries. Addressing the problem of IAS is urgent because the threat is growing daily, and the economic and environmental impacts are severe.

BOX 1: THE CONVENTION ON BIOLOGICAL DIVERSITY

The Convention on Biological Diversity (CBD) entered into force in 1993, and has now been ratified by nearly 190 countries. The CBD commits governments to take appropriate measures to conserve biological diversity, ensure the sustainable use of biological resources, and promote the fair and equitable sharing of benefits arising from the utilization of genetic resources. Under the CBD, governments agree to prepare national biodiversity strategies and action plans; identify genomes, species, and ecosystems crucial for conservation and sustainable use; monitor biodiversity and factors that are affecting biological systems; establish effectively managed systems of protected areas; rehabilitate degraded ecosystems; exchange information; conduct public information programmes; and carry out various other activities for implementing the CBD's objectives. A CBD secretariat has been established in Montreal. The Subsidiary Body on Scientific Technical and Technological Advice (SBSTTA) of the CBD meets periodically and addresses key issues, including invasive aliens. One major accomplishment of the CBD has been the Cartagena Protocol on Biosafety, which has implications for both invasive alien species and "Living Modified Organisms", the CBD's phrase for GMOs. The CBD has also established an interim financial mechanism, the Global Environment Facility, which provides approximately US$100 million per year to projects for implementing the Convention in developing countries; some of these projects address IAS (for example, in Galapagos Islands and Lake Victoria).

Numerous international instruments, binding and non-binding, have been developed to deal with certain aspects of the problem of IAS. The most comprehensive is the Convention on Biological Diversity (CBD - Box 1), which calls on its Parties to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats, or species" (Article 8h). A much older instrument is the 1952 International Plant Protection Convention (IPPC) which applies primarily to plant pests, based on a system of phytosanitary certificates. Regional agreements further strengthen the IPPC (Box 2). The IPPC was extensively revised in 1997 to meet some of the new challenges of plant pests. Other instruments deal with IAS in specific regions (such as Antarctica), sectors (such as fishing in the Danube), or vectors (such as IAS in ballast water, through the International Maritime Organization). Over 40 instruments or programmes are already in force, and many more are awaiting finalisation and ratification (Shine *et al.*, 2000).

BOX 2:
THE INTERNATIONAL PLANT PROTECTION CONVENTION

The IPPC, with 111 governments as Contracting Parties, aims "to secure common and effective action to prevent the spread and introduction of pests of plants and plant products, and to promote appropriate measures for their control". Defining pest as "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products", the Convention has been applied mainly to crops, but it also extends to the protection of natural flora. Thus the scope of the IPPC covers any invasive alien species that may be considered to be a plant pest. The IPPC Secretariat, housed at FAO in Rome, facilitates the development of internationally agreed standards for the application of phytosanitary measures in international trade to prevent and control the spread of plant pests (many of which are invasive alien species). The standards developed under IPPC are recognized by the World Trade Organization under the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement).

The expanding impact of IAS on both global economies and the environment suggests that these international instruments have been insufficient to prevent and combat IAS effectively. Furthermore, expanding international trade is moving ever more organisms more rapidly around the world, thereby increasing the threat of these species to native ecosystems and potentially overwhelming government efforts to prevent unwanted invasions.

2. WHY THE PROBLEM OF INVASIVE ALIEN SPECIES REQUIRES AN URGENT RESPONSE

2.1. The impacts of invasive alien species

The scope of biological invasions is global and the cost is enormous, in both environmental and economic terms. Invasive alien species have invaded and affected native biota in virtually every ecosystem type on Earth. These species have contributed to many hundreds of extinctions, especially under island conditions, whether it be on actual islands or ecological islands (such as freshwater ecosystems). The environmental cost is the irretrievable loss of native species and ecosystems.

Invasive alien species occur in all major taxonomic groups. They include viruses, fungi, algae, mosses, ferns, higher plants, invertebrates, fish, amphibians, reptiles, birds and mammals. Within those taxa, numerous species, including perhaps as many as 10% of the world's 400,000 vascular plants, have the potential to invade other ecosystems and affect native biota in a direct or indirect way (Rejmanek *et al.*, 2000).

Invasive species can transform the structure and species composition of ecosystems by repressing or excluding native species, either directly by out-competing them for resources or indirectly by changing the way nutrients are cycled through the system. IAS can affect entire systems; for example, when invasive insects threaten native species of insects, they can also have cascading effects on insect-eating birds and on plants that relied on the native insects for pollination or seed dispersal.

Increasing global domination by a relatively few invasive species threatens to create a relatively homogeneous world rather than one characterised by great biological diversity and local distinctiveness, thus affecting the capacity of ecosystems to adapt to changing conditions.

No criteria have yet been agreed for the minimum damage, spread or size of population needed for an alien species to be considered invasive. However, it is clear that a very small number of individuals, representing a small fraction of the genetic variation of the species in its native range, can be enough to generate, through its reproduction and spread, massive environmental damage in a new environment (Mack, 2000).

IAS have many negative impacts on human economic interests. Weeds reduce crop yields, increase control costs, and decrease water supply by degrading water catchment areas and freshwater ecosystems. Tourists unwittingly introduce alien plants into national parks, where they degrade protected ecosystems and drive up management costs. Pests and pathogens of crops, livestock and trees destroy plants outright, or reduce yields and increase pest control costs. And recently-spread disease organisms continue to kill or disable millions of people each year, with profound social and economic implications.

Considerable uncertainty remains about the total economic costs of invasions. However, estimates of the economic impacts on particular sectors indicate the seriousness of the problem. For example, the value of the fish catch in Lake Erie was US$600 million before the invasion of zebra mussels around 1986, but the value of the fish catch had declined to $200 million by the early 1990s, so a decline of $400 million worth of fish annually can be ascribed to the invasion of the zebra mussel (Bright, 1999). The varroa mite, a serious pest in honeybee hives, has recently invaded New Zealand and is expected to have an economic cost of US$267-602 million, forcing beekeepers to alter the way they manage hives. Beekeepers argue that had border rules been followed or had surveillance detected the mite earlier, the problem could have been avoided entirely. It now appears too late to eradicate the mite, requiring a mitigation plan that is expected to cost $1.3 million in its first stage. And a 1992 report by the Weed Science Society of America estimated that the total cost of non-indigenous weeds was between $4.5 billion and $6.3 billion. While the range of these figures indicates their uncertainty, they also indicate the order of magnitude of impact and argue for significant investments to prevent the spread and proliferation of these species. Other examples are listed in Box 3.

In addition to the direct costs of management of invasives, other economic costs include their indirect environmental consequences and other non-market values. For example, invasives may cause changes in ecological services by disturbing the operation of the hydrological cycle, including flood control and water supply, waste assimilation, recycling of nutrients, conservation and regeneration of soils, pollination of crops, and seed dispersal. Such services have both current use value and option value (the

BOX 3: INDICATIVE COSTS OF SOME INVASIVE ALIEN SPECIES (costs in US$)

SPECIES	ECONOMIC VARIABLE	ECONOMIC IMPACT	REFERENCE
Introduced disease organisms	Annual cost to human, plant, animal health in USA	$41 billion per year	Daszak et al., 2000
A sample of alien species of plants and animals	Economic costs of damage in USA	$137 billion per year	Pimentel et al., 2000
Salt Cedar	Value of ecosystem services lost in western USA	$7-16 billion over 55 years	Zavaleta, 2000
Knapweed and Leafy spurge	Impact on economy in three US states	$40.5 million per year direct costs $89 million indirect	Bangsund, 1999; Hirsch and Leitch, 1996
Zebra mussel	Damages to US and European industrial plants	Cumulative costs 1988-2000=$750 million to 1 billion	National Aquatic Nuisances Species Clearinghouse, 2000
Most serious invasive alien plant species	Costs 1983-92 of herbicide control in Britain	$344 million/year for 12 species	Williamson, 1998
Six weed species	Costs in Australia agroecosystems	$105 million/year	CSIRO, 1997 cited in Watkinson, Freckleton and Dowling 2000
Pinus, Hakeas, and Acacia	Costs on South African Floral Kingdom to restore to pristine state	$2 billion	Turpie and Heydenrych, 2000
Water hyacinth	Costs in 7 African countries	$20-50 million/year	Joffe and Cooke, cited in Kasulo, 2000
Rabbits	Costs in Australia	$373 million/year (agricultural losses)	White and Newton-Cross, 2000
Varroa mite	Economic cost to beekeeping in New Zealand	$267-602 million	Wittenberg and Cock, 2001

potential value of such services in the future). In the South African Cape Floral Kingdom, the establishment of invasive tree species has decreased water supplies for nearby communities and increased fire hazards, justifying government expenditures of US$40 million per year for manual and chemical control.

Although the loss of crops due to weeds or other alien pests may be reflected in the market prices of agricultural commodities, such costs are seldom paid by those doing the introductions. Rather, these costs are "externalities", i.e., costs that an activity unintentionally imposes on another activity, without the latter being able to extract compensation for the damage received. One special feature of biological invasions, as externalities, is that the costs of invasions are largely self-perpetuating, once they are set in motion. Even if introduction ceases, damage from the invasives already established continues and may well increase.

Most evidence of economic impact of invasive alien species comes from the developed world. However, the developing world is experiencing similar, if not proportionally greater, losses. Invasive alien insect pests, such as the white cassava mealybug and larger grain borer in Africa, pose direct threats to food security. Alien weeds constrain efforts to restore degraded land, regenerate forests and improve utilization of water for irrigation and fisheries. Water hyacinth and other alien water weeds affecting water use currently cost developing countries in Africa and Asia over US$100 million annually. Alien invasives pose a threat to over US$13 billion of current and planned World Bank funding to projects. The projects at risk are in the irrigation, drainage, water supply, sanitation and power sectors (Joffe and Cooke, 1998).

The costs of accidental introductions cannot be readily reflected by prices or markets. But even in the case of introductions involving deliberate imports to support agriculture, horticulture, forestry, and fisheries, market prices for seeds, plants, or foods seldom reflect the environmental risks associated with their introduction. Thus importers have little financial incentive to take account of the potential cost of the loss of indigenous species or disturbance to ecosystem functions. The policies developed to deal with conventional externalities involved in the general problem of biodiversity loss -- using such economic tools as taxes, subsidies, permits, and so forth -- may not always be well suited to deal with the problems caused by invasions. This point highlights the urgent need for new approaches to deal with IAS. These approaches may also be relevant to GMOs, at least conceptually.

2.2. Global trade and invasive alien species

The increased mobility of people and their goods bring an increased likelihood of movement of species around the planet, either deliberately in the form of commodities such as livestock, pets, nursery stock, and produce from agriculture and forestry, or inadvertently as species are transported in packaging, ballast water, and on the commodities themselves. Globalization of the economy is demonstrated by the increase in the value of total imports from US$192 billion in 1965 to US$6 trillion in 2000, a 28-fold increase in just over 30 years (World Bank, 2000). Imports of agricultural products and industrial raw materials increased from US$55 billion in 1965 to over $550 billion in 2002; these have the greatest potential to contribute to the problem of invasive species because unwanted species, especially insects and other invertebrates, may be physically transferred with the traded commodity.

International trade in goods and services between the current 146 Members of the World Trade Organization (WTO) is guided by the 1994 Uruguay Round Agreements. This regime provides for binding rules, enforced by a compulsory dispute settlement mechanism, designed to ensure that governments extend free market access to each other's products and services. Particularly relevant to alien species that are characterised as pests or diseases is the 1995 WTO Agreement on the Application of Sanitary and Phytosanitary Measures (the SPS Agreement), which allows Members to adopt national measures or standards to: (1) protect human, animal and plant life from the risks arising from the entry, establishment or spread of pests, diseases, or disease-carrying organisms or disease-causing organisms; and (2) prevent or limit other damage within the territory of the Member from the entry, establishment or spread of pests (Box 4).

Some governments are reported to be putting increasing pressure on their national quarantine agencies to adopt "acceptable" rather than minimum risks of introduction of invasive species as a means of stimulating trade. This policy change may accelerate the spread of alien species, especially as East-West trade within and between hemispheres becomes increasingly common. The growth of global economic activity will result in greater impacts because the spread of potentially invasive species will accelerate as the trade in biological products expands.

The globalization of trade and the power of the Internet offer new challenges to those seeking to control the spread of IAS, as sales of seeds and other organisms over the Internet pose serious new risks to the

BOX 4: WTO AGREEMENT ON SANITARY AND PHYTOSANITARY MEASURES

The SPS Agreement under the WTO is designed primarily to ensure that import restrictions are not used as a disguised form of commercial protectionism. It is not a mechanism to ensure that governments have adequate standards in place. However, the import restrictions must be based on scientific evidence, and applied only to the extent necessary to protect human, animal or plant life or health. The burden of proof remains with the recipient country. The Agreement seeks to protect countries from various pest species while promoting the principles of free and fair trade and makes provision for safe trade by promoting or requiring the use of:

- international standards as a basis for SPS measures;
- risk assessment based on scientific principles and evidence;
- consistency in the application of appropriate levels of protection;
- least trade restrictive alternatives;
- acceptance of equivalent measures; and
- transparency through notification of trade measures.

biosecurity of all nations. Controls on both import and export of species are required as part of a more responsible attitude of governments toward the potential spreading of invasive species around the world. While receiving countries must ensure that they are able to control the imported species, relatively few countries yet have effective controls in place. New Zealand is one outstanding example, having established the New Zealand Risk Management Authority with significant powers over proposed intentional introductions through a permit system (Shine *et al.*, 2000). Many countries have instituted customs and border controls, but these are only partially effective because of the sheer volume of trade and tourism.

Because global trade has such a profound influence by moving species around the world, it is particularly important to ensure that concerns about

IAS are built into relevant trade negotiations. Initial efforts are being made in this regard. For example, the Cartagena Protocol on Biosafety under the CBD is part of the global trade regime; it is to be mutually supportive of any agreements under the World Trade Organization (WTO). This Protocol is based on the principle 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 (MacKenzie et al., 2003). In any case, IAS are so important that they should form part of the WTO agenda, but the Secretariat of the CBD has not even been given Observer status at the WTO.

Some governments fear that controls over potentially invasive species may be considered trade restrictive. The WTO Agreement on Sanitary and Phytosanitary Measures (SPS) ensures that sanitary and phytosanitary domestic measures are consistent with the WTO obligations prohibiting arbitrary or unjustifiable trade discrimination. SPS trade restrictions must conform with international standards, guidelines and recommendations if those exist. For food safety, the reference organisation is the Codex Alimentarius Commission; for animal health and zoonoses, the International Office of Epizootics; for plant health, the Secretariat of the International Plant Protection Convention. For matters not covered by these organisations, "appropriate standards, guidelines and recommendations promulgated by other relevant international organizations open for membership to all Members" are acceptable. Many governments support mutual support among conventions and the SPS Agreement ad the Agreement on Technical Barriers to Trade under the World Trade Organization may offer useful opportunities for developing ways for the CBD and the WTO to collaborate more closely on issues of invasive alien species and trade in living modified organisms.

2.3. Human health and invasive alien species

The dynamism among invasive pathogens, human behaviour, and economic development are complex and depend on interactions between the virulence of the disease, infected and susceptible populations, the pattern of human settlements, and their level of development. Large development projects, such as dams, irrigation schemes, land reclamation, road construction and population resettlement programmes, have contributed to the invasion of diseases such as malaria, dengue fever, schistosomiasis and trypanosomiasis. The clearing of forests in tropical regions to extend agricultural land has opened up new possibilities for wider transmission of viruses that carry haemorrhagic fevers that previously circulated benignly in wild animal hosts. Examples include Argentine haemorrhagic fever, "Guaranito" virus, Machupo virus, and Basia virus. Some pathways for the biotic invasion are complicated. For example, the prevalence of lymphatic filariasis in the southern Nile Delta has increased 20-fold since the building of the Aswan dam in the 1960s. This increase has been due primarily to the increase in breeding sites for the mosquito vector of the disease following the rise in the water table caused by extending irrigation. The problem has been exacerbated by increased pesticide resistance in the mosquitoes, due to heavy agricultural pesticide use, and rural-to-urban commuting among farm workers. Thus invasive species combined with variations in inter-annual rainfall, temperature, human population density, population mobility and pesticide use all contribute to one of the most profound challenges of invasive species: the threat to human health.

Infectious disease agents often, and perhaps typically, are invasive alien species (Delfino and Simmons, 2000). Unfamiliar types of infectious agents, either acquired by humans from domesticated or other animals, or imported inadvertently by travellers, can have devastating impacts on human populations. Pests and pathogens can also undermine local food and livestock production, thereby causing hunger and famine. Examples:

- The bubonic plague spread from central Asia through north Africa, Europe, and China using a flea vector on an invasive species of rat.

- The viruses carrying smallpox and measles spread from Europe into the western hemisphere shortly following European colonization. The low resistance of the indigenous peoples to these parasites helped bring down the mighty Aztec and Inca empires.

- The Irish potato famine in the 1840s was caused by a fungus introduced from North America, with devastating impacts on the health of local people.

- Rinderpest, a viral disease, was introduced into Africa in the 1890s via infected cattle, subsequently spreading into both domesticated and wild herds of bovids throughout the savannah regions of Africa, changing the mammalian composition of much of the continent; up to 25% of the cattle-dependent pastoralists may have starved to death in the early 20th century, because rinderpest wiped out the cattle populations upon which they depended.

- The influenza virus has its origins in birds but multiplies through domestic pigs which can be infected by multiple strains of avian influenza virus and then act as genetic "mixing vessels" that yield new recombinant-DNA viral strains. These strains can then infect the pig-tending humans, who then infect other humans, especially through rapid air transport. The 2003 SARS epidemic may have involved this pathway.

Indirect health effects associated with IAS include the use of broad-spectrum pesticides against alien pests and weeds. Freed from their natural controlling factors, these organisms often reach sustained outbreak levels which encourages widespread and chronic pesticide use.

Some species have other indirect effects. In Tanzania *Lantana camara* thickets provide breeding grounds for tsetse flies infected with trypanosomes of domestic animals, and children are known to have died after eating its unripe berries. Pods of two *Prosopis* species introduced to Kenya were found to be a tasty food by local Turkana people soon after the species started to spread. However, "the pods recently appear to have turned poisonous" and serious stomach problems have been reported (Anon., 1997).

3. IAS AND GMO: SOME SIGNIFICANT PARALLELS

This paper has demonstrated some of the economic and ecological risks posed by non-native species that may become invasive. It has also discussed some of the measures that are being taken to deal with these risks. Some interesting parallels between IAS and GMOs are also worth exploring, both to better understand potential risks of GMOs and to consider some of the risk management measures that may be appropriate. Some have even pointed out that invasive alien species represent a threat to biodiversity that is far more immediately significant than the introduction of GMOs, though the latter ironically have received far more attention under the guise of biosafety (May, 2002). One suggestion was that the Biosafety Protocol under the CBD should also address the issues of invasive alien species and international trade (McNeely, 1999).

Research in Denmark, France, and the US has suggested that herbicide-tolerant genes can in principle "escape" from GM plants to nearby weedy relatives through pollen transfer. This could encourage the proliferation of "superweeds" which might turn out to be highly invasive. But researchers clearly are not yet certain whether a gene to improve one aspect of fitness, such as one conferring resistance to pests, herbicides, or drought, would necessarily make a weed or a GM crop more invasive.

This is not a simple issue. After all, non-modified introduced species contain millions of genes, while most GMOs have only a small part of their genome modified (albeit from very different life forms). Further, the genetic modification is designed for specific results desired by humans, such as pest resistance, herbicide resistance, or change in nutrient content; and these may not necessarily provide for better survival in the rigours of a competitive world. On the other hand, some scientists are concerned that the effects of GMOs may be much more insidious than those of introduced non-modified organisms (Firbank, 2003).

The recent ecological literature is replete with studies that demonstrate the fundamental requirement for caution regarding species introductions. The precautionary principle is clearly appropriate for GMOs, as indicated by the many problems caused by non-native species. Research on IAS clearly indicates that scientists simply do not know the answers to many fundamental problems, and indeed many of the ecological questions may not be answerable given the many variables associated with trying to predict the effects of species A in habitat B undergoing stress C under changing conditions of biotic and abiotic parameters D-Z. And if scientists cannot do that for the known biota, it probably will be much more difficult to predict the impacts of genomes with which no evolutionary history is shared.

One synthesis of published information, primarily from academic, peer reviewed journals, on the potential environmental risks and benefits of genetically engineered plants found that key experiments on both the environmental risks and the benefits are lacking (Wolfenbarger and Phifer, 2000). The complexity of ecological systems presents considerable challenges for experiments to assess the risks and benefits and inevitable uncertainties of genetically engineered plants. Collectively, existing studies emphasize that these can vary spatially, temporally, and according to the trait and cultivar modified. They point out that genetic modifications can potentially create changes that enhance the ability of an organism to become invasive. While genetic engineering transfers only short sequences of DNA relative to the entire genome of a plant, the resulting phenotype, which includes the transgenic trait and possibly other accompanying changes, can produce an organism novel to the existing network of ecological relationships, and therefore potentially invasive.

Some scientists believe that genetically modified organisms offer a new and more serious threat to biodiversity than do non-modified species. Some even define non-indigenous species as including genetically modified versions of native organisms (Ewel *et al.*, 1999). The crux of the issue is whether the GMOs are likely to be more competitive, or less competitive. After all, 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.

On the other hand, a 10-year survey of GM crops has concluded that they do not survive well in the wild and are no more likely to invade habitats than their unmodified counterparts (Crawley *et al.*, 2001). Crop plants typically do not have the characteristics of invasive species, being highly dependent on humans for their survival and putting more of their energy into production rather than adaptation. However, plants genetically modified in the future for traits such as drought resistance or pest resistance could be better at competing, requiring testing as they are developed. Some genetic modifications could increase weediness. The key is the trait that is introduced, not the fact of modification itself.

In the United Kingdom alone, at least 60 aliens have hybridised with indigenous species, producing additional environmental contamination from the unpredictable consequences of mixing thousands of new genes in a continuing process of illegitimate gene flow (Trewavas, 1999). Yet, although environmental activists label gene flow as unacceptable genetic pollution, there is no trampling of flowers or demonstrations at the international flower shows that are potent sources of new foreign pollen, nor demands for barriers miles thick at such shows to prevent cross-pollination by bees. Nor have there been requests for strict laws to prevent people introducing new foreign seeds into their gardens on the grounds that this would cause serious environmental damage by new hybridisation and subsequent gene flow. Ironically, the demonstrated risks of IAS have generated a much weaker response than the largely hypothetical risks of GMOs.

Trees are being genetically modified to produce less lignin, a component of the cell wall that confers strength and is a constituent of the tree's defence system. The purpose of producing trees with less lignin is that they will require less bleach and other toxic chemicals to break down the wood fibres into pulp, making the paper production process cleaner, cheaper, and less energy-consuming. Further, GM trees appear to grow more quickly than trees that have not been genetically modified, and they can be grown on land of marginal quality. On the negative side, such trees may become invasive species, and lowering the lignin content may well impair their pest resistance capabilities, requiring the use of additional pesticides (thus obviating any environmental benefits that may have been claimed) (Eichelbaum, *et al.*, 2001).

Aquaculture is also becoming a more important issue for those concerned about invasive alien species. Given the rate of over-fishing in the various fisheries of the world, it is not surprising that far greater investments are being made in aquaculture, the farming of fish, shellfish, and aquatic plants. Globally, aquaculture production has more than doubled over the past 10 years and now provides about a third of seafood consumed (Naylor *et al.*, 2001). In the US, over 100 species of aquatic plants and animals are being raised, in all 50 States, and output is expected to increase 5-fold by 2025 (Goldburg *et al.*, 2001). That's the good news. The bad news is that aquaculture is also leading to the introduction and establishment of many varieties of IAS, ranging from fish to pathogens, becoming a leading vector of aquatic IAS. As with most domesticated plants and animals in North America, the farmed aquatic species typically are not native to the area where they are being farmed. Some of the most difficult animal disease problems facing modern society involve the pathogens of these aquaculture species, causing economic losses to industry and spreading pathogens to the wild species in the region (Naylor *et al.*, 2000). This is no trivial matter, as it affects species of considerable importance. For example, a protozoan that causes whirling disease in trout was introduced to the USA in the 1950's, apparently through European Brown Trout. Release of the latter species spread the disease throughout prize fly-fishing streams in eleven western states, devastating some wild trout populations (Moyle and Light, 1996).

Salmon is particularly valuable and the most common species in aquaculture is the Atlantic salmon from the Eastern USA, which is now found in salmon farms from Chile to Norway; justifiable fears of escape and subsequent genetic swamping of a native species are increasingly being voiced (Naylor *et al.* 2000). Genetic modification could make the problem worse. For example, a company based in Massachusetts is proposing to market genetically modified salmon. Aqua Bounty Farms is raising Atlantic salmon (*Salmo salar*) modified to carry a growth-hormone gene from the Pacific Chinook salmon (*Oncorhynchus tshawytscha*) which is hooked to a powerful promoter sequence that boosts the growth rate of the fish so they can reach market size more quickly. However, some ecologists have warned that transgenic salmon could wipe out natural populations of related fish should they escape into the wild. Coastal aqua culture is already causing ecological damage by spreading fish diseases, modifying habitats, causing nutrient pollution, and through the escape of exotic farmed fish (Reichardt, 2000).

Lax regulations and insufficient management means that many aquaculture species are escaping, and becoming established in the wild, with profound ecological impacts. For example, North American bullfrogs have escaped from frog-leg ranches from Ecuador to Taiwan to Italy to become one of the world's worst invaders (Baker, 1995). Of course, measures are available to help prevent such invasions, such as culture in environments that are not suitable for reproduction, or growing sterile forms, but these measures are seldom implemented or enforced among the farmed species and even less so on those beyond human control, such as the well-known and expensive problem of the cane toad in Australia (van Dam *et al.*, 2000). On the other hand, biotechnology can be used to combat invasive species as well. Australian scientists are planning to insert a gene known as "daughterless" into invasive male carp in the Murray-Darling River, thereby ensuring that their offspring are male. The objective is to release them into the wild, sending wild carp populations into a nose dive and making room for the native species that are being threatened by the invasive carp. This is an example of using genetic modification to eradicate an invasive alien species. But if the gene is released into nature and starts to flourish, many other species could be negatively affected.

The Biosafety Protocol is fundamentally an effort to ensure that the ecological effects of GMOs are given proper attention. GMOs can be seen as alien organisms that may be invasive in some instances, and therefore are an important subset of the discussions of the alien invasives problem.

4. CONCLUSIONS

For millennia, the natural barriers of oceans, mountains, rivers and deserts provided the isolation essential for unique species and ecosystems to evolve. In just a few hundred years these barriers have been rendered ineffective by major global forces that have combined to help alien species travel vast distances to new habitats and become invasive alien species. The globalisation and growth in the volume of trade and tourism, coupled with the emphasis on free trade, provide more opportunities than ever before for species to be spread accidentally or deliberately. Customs and quarantine practices, developed in an earlier time to guard against human and economic diseases and pests, are often inadequate safeguards against species that threaten native biodiversity. Thus the inadvertent ending of millions of years of biological isolation has created major ongoing problems that affect both developed and developing countries.

Because of the potential for economic and ecological damage when an alien species becomes invasive, every alien species needs to be treated for management purposes as if it is potentially invasive, unless and until convincing evidence indicates that it is harmless in the new range. This view calls for urgent action by a wide range of governmental, intergovernmental, private sector, and civil institutions.

Because the diverse ecosystems of our planet have become connected through numerous trade routes, the problems caused by invasive alien species are certain to continue. As with maintaining and enhancing health, education, and security, perpetual investments will be required to manage the challenge of IAS, especially if GMOs are considered as a potential subset of IAS. A comprehensive solution for dealing with invasive alien species would include ten key elements:

1. An effective national capacity to deal with IAS. Building national capacity could include:

- Designing and establishing a “rapid response mechanism” to detect and respond immediately to the presence of potentially invasive species as soon as they appear, with sufficient funding and regulatory support;
- Appropriate training and education programmes to enhance individual capacity, including customs officials, field staff, managers, and policy makers;
- Developing institutions at national or regional level that bring together biodiversity specialists with agricultural quarantine specialists to collaborate on implementing national programmes on IAS; and
- Building basic border control and quarantine capacity, ensuring that agricultural quarantine officers, customs officials, and food inspection officers are aware of the elements of the Biosafety Protocol.

2. Fundamental and applied research, at local, national, and global levels. Research is required on taxonomy, invasion pathways, management measures, and effective monitoring. Further understanding on how and why species become established can lead to improved prediction on which species have the potential to become invasive, improved understanding of lag times between first introduction and establishment of IAS, and better methods for excluding or removing alien species from traded goods, packaging material, ballast water, personal luggage, and other methods of transport.

3. Effective technical communications. An accessible knowledge base, a planned system for review of proposed introductions, and an informed public are needed both within countries and between countries. Already, numerous major sources of information on invasive species are accessible electronically, and more could also be developed and promoted, along with other forms of media.

4. Appropriate economic policies. While prevention, eradication, control, mitigation and adaptation all yield economic benefits, these are in the form of public goods and hence are likely to be under-supplied. New or adapted economic instruments can help ensure that the costs of addressing IAS are better reflected in market prices. Economic principles relevant to national IAS strategies include ensuring that those responsible for the introduction of economically harmful IAS are liable for the costs they impose; ensuring that use rights to natural or environmental resources include an obligation to prevent the spread of potential IAS; and requiring importers of potential IAS to have liability insurance to cover the unanticipated costs of introductions.

5. Effective national, regional, and international legal and institutional frameworks. Coordination and cooperation between the relevant institutions are necessary to address possible gaps, weaknesses and inconsistencies, and promote greater mutual support among the many international instruments dealing with IAS. National legal and institutional frameworks should be designed along the lines recommended by Shine *et al.* (2000).

6. A system of environmental risk analysis. Such a system could be based on existing environmental impact assessment procedures that have been developed in many countries. Risk analysis measures should be used to identify and evaluate the relevant risks of a proposed activity regarding alien species, and determine the appropriate measures that should be adopted to manage the risks. This would also include developing criteria to measure and classify impacts of alien species on natural ecosystems, including detailed protocols for assessing the likelihood of invasion in specific habitats or ecosystems.

7. Public awareness and engagement. If IAS management is to be successful, the general public must be involved. A vigorous public awareness programme would involve the key stakeholders who are actively engaged in issues relevant to IAS, including botanic gardens, nurseries, agricultural suppliers, and others. The public can also be involved as volunteers in eradication programmes of certain IAS, such as woody invasives of national parks.

8. National strategies and plans. The many elements of controlling IAS need to be well coordinated, ensuring that they are not simply passed on to the Ministry of Environment or a natural resource management department. A national strategy should promote cooperation among the many sectors whose activities have the greatest potential to introduce IAS, including the military, forestry, agriculture, aquaculture, transport, tourism, health, and water supply. The government agencies with responsibility for human health, animal health, plant health, and other relevant fields need to ensure that they are all working toward the same broad objective of sustainable development in accordance to national and international legislation. Such national strategies and plans can also encourage collaboration between different scientific disciplines and approaches that can seek new approaches to dealing with IAS problems.

9. Build IAS issues into global change initiatives. Global change issues relevant to IAS begin with climate change but also include changes in nitrogen cycles, economic development, land use, and other fundamental changes that might enhance the possibilities of IAS becoming established. Further, responses to global change issues, such as sequestering carbon, generating biomass energy, and recovering degraded lands, should be designed in ways that use native species and do not increase the risk of the spread of IAS.

10. Promote international cooperation. The problem of IAS is fundamentally international, so international cooperation is essential to develop the necessary range of approaches, strategies, models, tools, and potential partners to ensure that the problems of IAS are effectively addressed.

Elements that would foster better international cooperation could include developing an international vocabulary, widely agreed and adopted; cross-sectoral collaboration among international organizations involved in agriculture, trade, tourism, health, and transport; and improved linkages among the international institutions dealing with phytosanitary, biosafety, and biodiversity issues related to IAS and supporting these by strong linkages to coordinated national programmes.

These ten elements, building on McNeely *et al.* (2001), could be modified to incorporate issues addressing genetically modified organisms, thus ensuring that the clear and present danger of IAS is addressed in ways that build the capacity to address any future problems that may arise through new applications of biotechnology.

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