Toward a Global Information System for Invasive Species

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The growing frequency and impact of biological invasions worldwide threaten biodiversity, ecosystem functioning, resource availability, national economies, and human health (Ruesink et al. 1995, Simberloff 1996, Vitousek et al. 1997). Organisms are spreading into new regions at unprecedented rates. As a result, hundreds to thousands of nonindigenous species of invertebrates, vertebrates, plants, bacteria, and fungi have become established in all but the most remote areas of the planet (Vitousek et al. 1997). Recent examples are abundant and, in some cases, alarming. Cholera bacteria and toxic dinoflagellates have been discovered in the ballast waters of cargo ships (McCarthy and Khambaty 1994, Hallegraeff 1998). Asian tiger mosquitos—vectors of yellow fever and encephalitis—have spread to new continents in imported truck tires (Moore et al. 1988). Pasture and crop lands in Australia are being invaded by *Parthenium*, an aggressive Caribbean weed that causes severe allergic reactions in livestock and humans (Evans 1997). Rapid and widespread dieoffs of native freshwater mussels are occurring in the wake of the zebra mussel invasion in North America (Ricciardi et al. 1998). [AQ4]Hardwood trees in American cities are being killed by Asian longhorned beetles introduced with wooden packing crates (Haack et al. 1997).

Every year, one-fourth of the US agricultural gross national product is lost to the impact and control costs of a growing variety of foreign pests (Simberloff 1996). The problem will likely worsen with time because of climatic changes that promote species migrations (Dukes and Mooney 1999) and expanding world trade, which shuttles organisms both deliberately and unintentionally across natural geographic barriers via air, land, and ship traffic. Even now, the accelerated pace of international trade overburdens risk assessment, inspection, and the law enforcement needed to prevent harmful introductions (Jenkins 1996). Both early detection and effective control depend on the availability of up-to-date information that keeps pace with new invasion threats.

Retrieving critical information about the spread, impact, and control of invasive species has always been difficult because much of this information is buried in disciplinary journals from many different fields (e.g., ecology, weed science, crop science, wildlife management, and biogeography) or in obscure government documents and technical reports ("gray literature") that are not widely accessible. An increasing amount of information is also being stored in electronic repositories. The diffuse distribution and variable quality of this information limit the ability of managers to combat invasions.

In October 1998, a workshop was convened at the University of Tennessee at Knoxville to discuss the creation of an Internet-based global information system that would provide comprehensive and readily accessible information to aid monitoring, risk assessment, and control of invasive species. The goals of the workshop were to determine how this system should address management and research needs and to identify the system's key elements. Participating in this meeting was a diverse group of resource managers, database managers, and academic researchers. In this article, we briefly summarize their ideas in the hope of encouraging concerted action against the invasive species problem.

Why a global information system?

Traditional approaches to gathering and disseminating biological information are clearly inadequate to deal with the global onslaught of introduced species. The print publication process is too slow, and the relevant information (including maps, photos, and data sets) is often too large or complex for normal print media. However, electronic media offer an efficient solution for the storage, analysis, and rapid distribution of a potentially huge amount of biological data (Schalk and Oosterbroek 1996). Consequently, numerous electronic databases have been developed recently to disseminate information on invasive species; most of these are available on the Internet (Table 1; Ridgway et al. 1999). Because these databases operate independently and are oriented toward particular user groups (e.g., resource managers, researchers, or the general public), the information they contain is variable in scope and quality and has a regional focus. Although they can be of great value in promoting awareness of invasive species problems, regional databases are insufficient for tracking harmful species that can suddenly appear in areas

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far from their native ranges (e.g., the Asian longhorned beetle, European green crab, and toxic marine dinoflagellates). They are also inefficient at helping managers deal with diverse groups of invaders that interact to exacerbate impacts (Simberloff and Von Holle 1999). We contend that a coordinated global approach is necessary to detect and manage the large-scale movement of invaders.

The growing number of independent electronic databases is itself a compelling argument for a coordinated system. Table 1 lists some of these databases, many of which provide hyperlinks to other valuable information resources. This list is not exhaustive because we are undoubtedly not aware of all electronic databases that are currently available. An essential first step toward a global information system will be to identify all current databases and all taxa and regions that require databases. Some electronic databases are available on CD-ROM only and are not accessible over the Internet, and other databases are just being put into electronic form (Jacono and Boydstun 1998, Ridgway et al. 1999). Most existing online databases are devoted to nonindigenous terrestrial plants, particularly agricultural pests in the United States (Table 1). In contrast, we found few online databases for marine invaders; however, more will likely emerge in response to the growing number of invasions in estuarine and coastal habitats worldwide (Ruiz et al. 1997).

A coordinated system linking invasive species databases

Rather than an all-encompassing data repository, we propose a system that will electronically link all independently operated databases available on the Internet, with the individual databases remaining independent. The system's primary goals would be to function as both a comprehensive registry and a search engine for information on invaders, providing "one-stop shopping" for users. As new technologies for data retrieval are developed, the system could evolve into a meta-database—that is, a system that allows researchers to analyze data pooled from multiple databases.

Researchers from many scientific disciplines are already investing in ways to facilitate the analysis of burgeoning amounts of scattered electronic data. For example, the National Center for Biotechnology Information has a search and retrieval system (www.ncbi.nlm.nih.gov/Entrez) that integrates molecular biology information (e.g., nucleotide and protein sequences) from various independent databases. Furthermore, a software program ("The Species Analyst"; habanero.nhm.ukans.edu/SpeciesAnalyst) has been developed at the University of Kansas Natural History Museum for searching and pooling records from disparate biodiversity databases, including those compiled using incompatible software (Kaiser 1999). The program is based on a data retrieval protocol (known as Z39.50) that libraries use to share bibliographic information. In fact, taxonomists around the world are planning to link biodiversity databases into a single searchable archive of all the world's 1.7 million described species—a veritable "catalogue of life" (Reichhardt 1999). Similarly, the Organisation for Economic Co-operation and Development plans to develop software to link databases that contain geographical, ecological, and genetic data on biodiversity to create a global biodiversity information facility (Redfearn 1999).

Through a coordinating body (e.g., the International Union for the Conservation of Nature), the global system we envision could provide standards for new invasive species databases that would reduce overlap, increase technical compatibility, and ensure the consistent usage of nomenclature and tabular data. Although some standard formats already exist (e.g., those used by the series "Biological Flora of the British Isles" and "The Biology of Canadian Weeds," which are published regularly in the *Journal of Ecology* and the *Canadian Journal of Plant Science*, respectively), we propose a different set of information categories for inclusion in developing databases (see box page 242).

Diagnostic information. Sufficient diagnostic information should be included so that users can readily identify newly introduced species. Photographs and illustrations of the important life stages of the invader would facilitate identification and management. For certain plants and other organisms, taxonomic descriptions must be sufficiently detailed to distinguish the particular varieties or subspecies that are invasive.

Current distribution. Maps of the native and invaded ranges of each listed species should be provided, based on information that is updated regularly (e.g., data from field surveys incorporating geographic information systems technologies). These data can be used to interpret an invasive species' ability to spread into particular regions, allow calculation of its rate of dispersal, and enable prediction of its future range (Mack in press). For example, the appearance of an invader in one region may indicate its potential to spread into neighboring areas or into distant regions connected by trade traffic. Therefore, future invasion threats may be identified from current information on the presence of invasive species in potential donor regions (Ricciardi and Rasmussen 1998, Ricciardi and MacIsaac 2000). Furthermore, knowledge of the current distributions of invaders would help resource managers set priorities and project management costs—the first steps in seeking funding for combating invasive species.

Basic biology. Biological information should include the invader's environmental preferences and tolerances at all critical life stages. Knowledge of physico-chemical barriers to colonization (e.g., the temperature or the number of frost-free days required for reproduction and development) enables managers to assess which habitats are at risk

Table 1. Examples of invasive species databases available on the Internet.

Database (Agency)	Web site (URL)	Coverage
World Weeds Database (Forestry Institute, Oxford University, United Kingdom)	www.plants.ox.ac.uk/ofi/wwd/pweeds.htm	More than 2400 plant species worldwide
Plants Database (USDA[a] Natural Resources Conservation Service)	plants.usda.gov/plantproj/plants/index.html	Terrestrial and aquatic plants in the United States
Crop Profiles Database (USDA)	pestdata.ncsu.edu/CropProfiles	Arthropod and plant pests of US agriculture
Weeds Gone Wild (Plant Conservation Alliance's Alien Plant Working Group)	www.nps.gov/plants/alien/index.htm	Terrestrial plant invaders of US parks
Southwest Exotic Plant Mapping Project (USGS–BRD[b])	www.usgs.nau.edu/swemp/species_intro.htm	Primarily terrestrial plants in the southwestern United States
CalWeed Database (California State Department of Food and Agriculture, California Interagency Noxious Weed Coordinating Committee, US Bureau of Land Management, University of California–Davis)	endeavor.des.ucdavis.edu/weeds	Terrestrial plants in California
North American Non-Indigenous Arthropod Database (USDA–APHIS[c])	www.plantprotection.org/rppc/NANIAD.html	Terrestrial arthropods in the United States
INVADERS Database System (University of Montana)	invader.dbs.umt.edu	Terrestrial and aquatic plants in the northwestern United States
Biota of North America Program (North Carolina Botanical Garden, University of North Carolina)	www.bonap.org	Terrestrial and aquatic plants of North America
National Agricultural Pest Information System (USDA–APHIS)	www.ceris.purdue.edu/napis	Terrestrial plants and invertebrates in the United States
Exotic Forest Pest Information System for North America (North American Forest Commission)	www.exoticforestpests.org	Weeds, arthropods, and pathogens of US forests
Weeds in New Zealand (Environment Bay of Plenty Regional Council, New Zealand)	www.boprc.govt.nz/www/green/weedindx.htm	Terrestrial and aquatic plants in New Zealand
Releases of Beneficial Organisms in the United States and Territories (USDA)	www.ars-grin.gov/nigrp/robo.html	Terrestrial invertebrates in the United States, including biological control agents and pollinators
Slow the Spread Gypsy Moth Database (Department of Entomology, Virginia Tech)	www.ento.vt.edu/STS	Spatial and temporal data on the spread of the gypsy moth in the United States
Invasive Plants of Canada Project (Parks Canada)	magi.com/~ehaber/ipcan.html	Terrestrial and aquatic plants in Canada
Hawaiian Ecosystems at Risk project (USGS–BRD, University of Hawaii)	www.hear.org	Terrestrial and aquatic plants, invertebrates, and vertebrates in Hawaii
Invasive Exotic Pest Plants in Tennessee (Southeast Exotic Pest Plant Council)	www.webriver.com/tn-eppc/exlist.html	Terrestrial and aquatic plants in Tennessee
Non-indigenous Species in the Gulf of Mexico Ecosystem (Gulf of Mexico Program and Gulf Coast Research Laboratory Museum	www.ims.usm.edu/~musweb/invaders.html	Viruses, invertebrates, fishes, birds, mammals, and herpetofauna in the Gulf of Mexico region
National Marine and Estuarine Invasions Database (Smithsonian Environmental Research Center)	www.serc.si.edu/invasions/nis.htm	Marine invertebrates, vertebrates, plants, and algae in the United States
Invasive Marine Pests Database (CSIRO[d], Centre for Research on Introduced Marine Pests)	www.marine.csiro.au/CRIMP/isppfram.html	Marine invertebrates, algae, plants, and fishes in Australia
Non-indigenous Estuarine and Marine Organisms Database (Coastal Research and Planning Institute, Klaipeda University, Lithuania)	www.ku.lt/nemo/mainnemo.htm	Marine invertebrates, algae, plants, and fishes in the Baltic Sea region
Group on Aquatic Alien Species (Zoological Institute, Russian Academy of Sciences, St Petersburg)	www.zin.ru/projects/invasions/index.html	Aquatic invertebrates in central and northern Europe
Directory of Non-native Marine Species in British Waters (Joint Nature Conservation Committee, United Kingdom)	www.jncc.gov.uk/marine/dns/default.htm	Marine invertebrates, algae, and plants in the United Kingdom
Database on Introductions of Aquatic Species (Food and Agriculture Organization of the United Nations)	www.fao.org/waicent/faoinfo/fishery/statist/fisoft/dias/index.htm	Fish, mollusk, and crustacean species introduced globally for commercial purposes
Sea Grant Nonindigenous Species Site (NOAA[e], Great Lakes Sea Grant Network)	www.ansc.purdue.edu/sgnis	Freshwater plants, invertebrates, and fishes in the United States
Nonindigenous Aquatic Species information resources (USGS–BRD, Florida)	nas.er.usgs.gov	Aquatic plants, invertebrates, and vertebrates in the United States
Aquatic, Wetland and Invasive Plant Information Retrieval System (University of Florida, Center for Aquatic and Invasive Plants)	aquat1.ifas.ufl.edu/database.html	Aquatic and wetland plants in the United States
Invasive Species in the Pacific (IUCN[f] Invasive Species Specialist Group)	www.issg.org/islinv1/index.html	Aquatic and terrestrial invertebrates, vertebrates, and plants in the Pacific region
Plant Viruses Online (Virus Identification Data Exchange Project, Australian Centre for International Agricultural Research)	biology.anu.edu.au/Groups/MES/vide/refs.htm	Plant viruses worldwide

[a]USDA, US Department of Agriculture
[b]USGS–BRD, US Geological Survey–Biological Resources Division
[c]APHIS, Animal and Plant Health Inspection Service
[d]CSIRO, Commonwealth Science and Industrial Research Organisation
[e]NOAA, National Oceanic and Atmospheric Administration
[f]IUCN, International Union for the Conservation of Nature

Key information for a standardized invasive species database

Taxonomy (Order/Family/Genus/Species):
- Common names
- Species synonyms
- Morphological/genetic varieties (if relevant)
- Diagnostic information (including photos, detailed illustrations)

Current distribution and habitat types (including maps)
Basic biology:
- Life cycle
- Feeding and nutrition
- Modes of reproduction
- Abundance (or area occupied and productivity)
- Environmental tolerances and optimal growth conditions

Biotic associations (pathogens, parasites, and commensals)
Modes of dispersal
Documented impacts (on populations, communities, ecosystems)
Economic impacts and control costs
Control options
Bibliography (electronically linked)
Contact information for expert authorities

of being invaded by a species (e.g., Patterson et al. 1982). Similarly, the database should include information on predators, parasites, and other biological enemies in the invader's native range.

Dispersal. Information concerning the specific modes of transport for an invader is required for effective control (Ruesink et al. 1995, Hallegraeff 1998). Humans are chiefly responsible for the intercontinental movement of nonindigenous species and continue to play important roles in the regional spread of these species after they become established. For example, recreational boating is the primary vector of long-distance overland dispersal for several aquatic invaders, including the zebra mussel and the Eurasian watermilfoil (Buchan and Padilla 1999). The brown tree snake, which is responsible for extinctions of native birds and reptiles on Guam, is being transported to other regions in the wheel wells of aircraft (Engeman et al. 1998). Such information helps managers to identify and regulate human activities that promote the spread of harmful invaders.

Impacts. Information on the impacts of invaders is essential for setting management priorities (Hiebert 1997). Presently, there is no standardized conceptual framework for measuring and predicting impact. To develop such a framework, Parker et al. (1999) recommended that the effects of an invader be quantified at multiple levels: on individuals, on populations (e.g., changes in genetics, abundance, and demographics), on communities (structure and function), and on ecosystems (abiotic processes). Few of these data may be available initially, but even fragmentary information is useful; for example, an organism's history of impact in a previously invaded region could be used to make tentative predictions of its impact elsewhere (e.g., Grosholz and Ruiz 1996, Ricciardi et al. 1998).

Another complication in predicting impacts is that combinations of invaders may have synergistic effects at the community and ecosystem levels (Simberloff and Von Holle 1999, Ricciardi and MacIsaac 2000). Therefore, data for each invader should include a list of species known to facilitate its persistence and enhance its impact. Particular attention should be paid to the potential change in invasiveness of an established organism as a result of the introduction of another species (e.g., ornamental figs introduced to Florida have spread following the subsequent introduction of their requisite pollinators; McKey and Kaufmann 1991) and to the impact of "hitchhiking" organisms (i.e., parasites, commensals) associated with another introduced species. An example of a hitchhiking organism is *Myxobolus cerebralis*, the myxosporean parasite that causes salmonid "whirling disease" and is transported with introduced trout (Bergersen and Anderson 1997). Risk assessment of such interacting groups of invaders would be aided by access to multiple linked databases.

Control methods. Readily accessible information on control methods would greatly benefit managers, not only by offering potential solutions but also by helping them to avoid adopting strategies that have already been tried and failed. In addition, managers who must deal with species for which few controls have been tested could gain insight from information on how taxonomically and ecologically similar pests have been treated. The global system should also contain information on the effects of deliberate release of exotic biological control agents (e.g., nonindigenous predators and parasites) so that their effectiveness and impact on both the target species and nontarget organisms could be monitored. The US Department of Agriculture has already developed an electronic archive of some biological control agents currently in use (Table 1).

Bibliographies and expert contact information. Each database should cite pertinent studies or provide links to extensive bibliographies for high-priority invaders. It may be necessary to form a special working group to locate relevant gray literature and find funding to make this literature accessible over the Internet. A database should also give enough information to permit independent inquiries and facilitate the verification of voucher specimens; it should therefore provide e-mail addresses of cooperating authorities (e.g., "Plant Taxonomists Online," www.unm.edu/~jmygatt/waissrch2.html), museums, herbaria, and similar resources.

Filling information gaps: data acquisition and quality control

The primary goal of the global information system should be to provide rapid access to as many databases as possible. After the system has been launched, it should strive to fill information gaps. Given that most relevant data for invaders would be ultimately pooled and organized within the system, research needs will be clearly evident. The system's coordinating body could help compile existing databases by soliciting information from investigators and managers. Electronic submission forms could be used for this purpose; however, for quality control, standards for information submission would be needed. In addition, the coordinating body could organize a listserver (i.e., an electronic "bulletin board") to allow users to post comments and queries promptly.

Any database is a compromise between being so encyclopedic that it is cumbersome and filled with irrelevancies and so terse and narrowly focused as to be superficial. The coordinating body and various database managers will need to judge what data are useful (e.g., following the box page 242), both now and in the future. An important task will be to verify submitted data. Ideally, this work would be handled by a panel of international authorities, professional societies, or both. At the global scale, data verification would include checking taxonomic revisions (e.g., synonymies), validating the efficacy of control methods, and confirming new invasion vectors, routes, and donor regions. At the regional scale, verification would include confirmation of sightings and of the continued presence of an invader because some introduced species eventually disappear from a region. Impacts must also be validated regionally, and the economic cost of each invasion should be estimated.

The global system we envision would have relatively modest financial costs for its creation, maintenance, and growth. Ideally, these could be met by a United Nations agency such as the United Nations Environmental Programme; otherwise, the system could be maintained by a national governmental agency, such as the US Geological Survey's Biological Resources Division or the Norwegian Ministry of the Environment. The cost of such a system would be trivial compared to the value of preventing a single major biological invasion.

Benefits to society and the biosphere

A coordinated system of invasive species databases would have multiple benefits. First and foremost, such a system would help to organize the increasing volume of information on invaders. As a single gateway to this information, it would reduce search time and provide users with access to a broad range of invasive species data. Moreover, it would be a valuable research tool for the analysis of factors contributing to invasion success, for measuring rates of spread, and for comparing impacts across multiple sites—thus improving scientists' ability to predict the impact of newly introduced species. The system would clarify spatial and temporal patterns of invasion on regional, national, and global scales. By tracking the movements of invasive species, it would help managers to assess risk and to more effectively allocate limited resources toward preventing spread and enabling early eradication. In particular, it could serve as an early warning system by monitoring harmful invaders that threaten biodiversity hotspots, agricultural systems, or human health. Prioritizing which species to monitor would have to be done regularly based on new data on their distribution and impact. Although priority lists will vary regionally, a global information system would facilitate species comparisons for prioritization because all relevant data would be accessible from one Web site.

Finally, a global information system would promote public awareness of invasion problems. The importance of this role cannot be underestimated, given that virtually all species introductions are caused by human activity. It is noteworthy that, unlike other environmental issues, the need to address the problem of invasive species is recognized equally by stakeholders in commerce, agriculture, forestry, and conservation (Holt 1996). The development of a global information system would provide a unique opportunity for cooperative action at national and international levels. The time for such action has never been more propitious.

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