A GLOBAL DATABASE: THE KEY TO WEIGHING ON-THE-GROUND INVASIVE SPECIES IMPACTS

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ABSTRACT

Natural area managers are currently confronted with a bewildering array of potential sources of information on invading non-indigenous species. At the same time, they often lack sufficiently comprehensive tools to assess current and likely impacts of these invaders in order to prioritize control activities. Existing tools to help evaluate impacts are primarily lists of characteristics of previous invaders and of sites of concern; other tools consist of formal risk assessment procedures. We review the gamut of ecological and genetic impacts that invaders can produce, some of which are not encompassed by existing evaluation tools. Actually measuring the components of impact is often not trivial, but previous studies provide much guidance. Decision theory has not been broadly applied to management of invasive non-indigenous species, even though it provides algorithms that could be used in this context and that would rationalize actions in terms of risks and costs. Risk assessment, evaluation of potential impacts, and decision-making would be greatly facilitated by a global database. We discuss the characteristics

of such a database. Properly populated and maintained, a global database could provide much of the information a site-manager would need to determine which non-indigenous species to manage and how to manage them.

Index terms: decision theory, global database, impact, non-indigenous species

INTRODUCTION

The threats posed by invasive non-indigenous species (NIS) to natural systems and native species are a major concern of conservation biologists and natural area managers. Next to habitat loss, invasive NIS are thought to cause the greatest loss of native biodiversity (Walker and Steffen 1997); a survey in 1986-87 ranked plant NIS as the greatest threat and animal NIS as the fourth greatest threat to U.S. National Parks (U.S.Congress 1993). These invaders span all taxa, from invertebrates to vertebrates, non-vascular to vascular plants, and bacteria to fungi. They invade freshwater, marine, and terrestrial communities across the globe. Examples include vascular plants like catclaw mimosa (*Mimosa pigra*), which has formed virtually monospecific stands over large areas in northern Australia (Lonsdale et al. 1989); invertebrates like the zebra mussel (*Dreissena polymorpha*), which has caused local extirpation of native mussels and changed water quality in the Great Lakes and rivers and lakes throughout the East and Midwest (Ricciardi et al. 1998); vertebrates such as the Nile perch (*Lates nilotica*), which has caused the extinction of over a hundred native cichlid fishes in Lake Victoria (Goldschmidt 1996), and algae such as *Caulerpa taxifolia*, which has rapidly covered over 4,000 ha of northern Mediterranean soft bottom, locally eliminating meadows of the native seagrass *Posidonia oceanica* and associated plant and animal species (Meinesz 1996).

However, many species also invade natural areas but appear not to threaten their composition or function significantly. These include two host-specific seed-eating beetles (*Acanthoscelides puniceus* and *A. quadridentatus*) introduced in Australia to control *Mimosa pigra*. No impact has been detected on *Mimosa pigra* (they ingest about 1% of the seeds) or other species, but they are widespread and persist, including in natural habitats invaded by the mimosa (M. Lonsdale, unpubl. obs.). In New Zealand, two non-indigenous composites (*Mycelis nivalis* and *Hypochoeris radicata*) are both widespread, including in natural habitats, and have not been perceived as having an impact on native species (I. Atkinson, pers. comm.). Dandelions (*Taraxacum* spp.) appear to be similarly widespread but innocuous in national parks of the United States (R. Hiebert, pers. obs.)

Defending natural areas from invasion by new NIS and controlling existing invaders is a complex, expensive, long-term proposition. At the site level, a manager needs to identify which species are both causing impacts to site resources and feasible to control. From that group, managers must then determine the priorities for allocation of resources for species control, with respect to both species and locations. Finally, managers must also identify invasive species that are not yet causing impacts in an area of interest but have a high probability of doing so as they spread. At the regional scale, program managers most often need to select the species or site(s) on which to concentrate efforts. At the national level, decisions must be made on what regions are most threatened and where cost-effective support should be provided.

Thus, the natural areas manager needs to be equipped with a range of accurate and usable information on numerous species. These data include the origin of the invasive NIS, its characteristics, current range, abundance, and rate of spread. The manager also needs information on the types and severity of impacts that an invasive NIS can cause and how those impacts will influence successful attainment of management goals. Because not all species constitute the same threat at any given time, tools for estimating likely impacts are critically necessary for prioritization of resources and effort.

Some information and tools are presently available that identify species likely to require control for some groups of species and for a few countries. The International Union for the Conservation of Nature has formed an international exotic species task force. Data on non-indigenous species by country are confined mainly to North America, Europe, Australia, and

Oceania and are of variable quality (D'Antonio 1997). Lists of species that are known to be invasive and pose serious threats to native biota and ecological processes are mostly confined to vascular plants (e.g., the lists of the Exotic Pest Plant Councils of Florida, California, the Pacific Northwest, and Tennessee). Lists of aquatic nuisance species are now being developed (e.g., <http://nas.er.usgs.gov>). For other groups of organisms, known invasive taxa are usually confined to species that have already been perceived to have devastating and widespread impacts.

Most data on the impact of invasive NIS have relied on some combination of the area invaded, number of invasion sites, and abundance of the invader in the new site. While species that become dominant over large areas (e.g., kudzu [*Pueraria montana*]) or cause widespread mortality of a native dominant (e.g., chestnut blight [*Cryphonectria parasitica*]) are likely to have ecological impacts on other species present, few of these impacts have been directly documented (Parker et al. 1999). A range of impacts at several levels have been documented for specific species at specific sites, but these are often not easily measured or even noticed (Parker et al. 1999). We summarize several of these impacts below. Since a site-based manager is likely to encounter more than one NIS with the potential to invade over a large area, evaluation of differential impacts of the NIS on the species, communities, or processes identified in management goals would allow clear, defensible prioritization of efforts. A rationale for resources needed to control the invader(s) would also be clear.

Once impacts and potential impacts have been estimated, this information plus other data (e.g., on costs of possible management options) can be marshaled to decide which species to attempt to manage, how, and the resources to be devoted to each. A few systems for making such decisions are currently available for site-based or regional prioritization of control efforts. Hiebert and Stubbendieck (1993) provide a method for ranking vascular plants at the site level that has been modified to rank non-indigenous animals at both site and regional levels (Hiebert, unpub. data; http://www.aqd.nps.gov/pubs/ranking/). The Nature Conservancy has been developing a similar system for ranking non-indigenous plant species on a national scale (Randall et al. 1996). The Australian government has adopted a weed risk assessment program (WRA) that evaluates whether new imported plant species are likely to be invasive (Pheloung 1995). There are also efforts to develop predictive models of likely invaders (e.g., Rejmánek and Richardson 1996, Reichard and Hamilton 1997). However, these systems, while the best tools currently available, allow only limited evaluation of likely local ecological impacts. Though such an evalution would be critical to determining local resource allocation priorities, it would not be sufficient. Additionally, all these efforts are limited in regional or taxonomic scope. Below we discuss a more formal decision theory, developed in other disciplines, that may inform and rationalize efforts to manage NIS.

We argue here that managers and policy-makers will be unable to make critical management, budget, and conservation decisions without access to a more comprehensive database. We suggest components of this database that would allow the development of more accurate determinations of likely impacts of NIS in new habitats. We also describe existing sources of information to help populate this database. Because the best predictor of invasiveness of a species has been shown to be whether it has invaded elsewhere outside its native range (Forcella et al. 1986, Crawley 1989, Scott and Panetta 1993, Reichard and Hamilton 1997), compilation of a global list even without the associated data would be a very useful predictive tool for natural area managers.

EXISTING TOOLS TO EVALUATE RELATIVE IMPACTS

Several models have been developed specifically to predict which species or types of species have a high potential to be invasive or to evaluate the relative threat and impacts of NIS to a site or a region. These can be categorized as predictive models, ranking systems, and risk assessment techniques.

An example of a predictive model is that developed for woody plants by Reichard and Hamilton (1997). This model is based on taxonomic, ecological, and species attributes.

Taxonomic traits include relationship to existing weeds. Ecological attributes include geographic origin and invasiveness elsewhere. Species attributes include vegetative reproduction, growth rate, and seed germination requirements. The rationale is to provide a quantitative tool to target species for prevention of invasion.

Hiebert and Stubbendieck (1993) have developed a system to rank non-indigenous plants based upon current impacts to a site or region and the innate ability of a species to be a pest (species and ecological characteristics). The system includes the range and area factors and attempts to measure the per capita impact of the impact equation proposed by Parker et al. (1999) and discussed below. The resulting threat/impact ranking is weighed against a score for feasibility of control derived from attributes including the degree of success of control in other areas, saturation in surrounding area, range, abundance, and impacts of control on non-target organisms. This system has been applied to over ten U.S. national park areas based upon both quantitative and qualitative surveys. It has also been used at a state scale and has been modified to rank non-indigenous animals (R. Hiebert, pers. comm.).

A similar system is being developed by The Nature Conservancy to rank non-indigenous plant species at the national and continental scale (Randall et al. 1996). Components include (1) impact on natural areas, (2) conservation significance of invaded communities, (3) species characteristics, (4) distribution and abundance in the region, and (5) management potential.

The Australian WRA assesses the risk that a plant will become invasive by asking, for each species proposed for introduction, 49 ‘yes/no’ questions pertaining to its biology, ecology or agricultural history (Pheloung 1995). Points are given for positive answers to questions implying weedy attributes and deducted for answers indicating attributes of non-invaders. The resulting score is used to recommend that the application for introduction is either accepted and the plant allowed entry to Australia, evaluated further, or rejected and the plant is placed on a list of prohibited imports. The questionnaire and scoring system are currently available on the Internet (<http://www.agric.wa.gov.au/progserv/plants/weeds/Weedsci.htm>).

Output from application of these tools and models can be used to populate many fields of the global database proposed below. Mining of these and other existing data will be labor-intensive and time-consuming. Special care will be required to maintain quality control.

NEW CONSIDERATIONS IN MANAGEMENT DECISIONS

A. More comprehensive treatment of impacts

Area of occupancy is the most commonly used measure of impacts of NIS that are invasive in natural areas. It is often the easiest metric to measure. And it is surely a component of any reasonable measure of existing impact, if not future impact. However, area is usually an insufficient metric to represent ecological impact by itself, for at least two reasons. First, two different species covering the same area can obviously have different impacts: for example, one might be a grass that intensifies wildfire, the other a tree that suppresses it. Secondly, an NIS occupying a very small area might nevertheless have (in some sense) a major impact, if that area happens to contain the only population of a native species, and the NIS drives it to extinction.

The highest priority in conservation efforts is often saving species. From this perspective, the area an NIS occupies is not as important as the number of species it affects, especially the number of species it eliminates locally and, at worst, globally.

Finally, some ecosystem ecologists consider the greatest impacts to be changes in ecosystem properties (e.g., properties of nutrient cycles or fire regimes). Thus, a nitrogen-fixing plant invading area X of a region with nitrogen-poor soil and no native nitrogen-fixers would have a greater impact than a non-nitrogen-fixing plant invading exactly the same area. For some adherents of this view (e.g., Vitousek 1990), the ultimate impact still seems to be what happens to species rather than what happens to the ecosystem properties themselves; it is just that changed ecosystem properties (= changed "fundamental rules of existence for all organisms in the area," Vitousek 1990, p. 8) are likely to affect many species. For other authors, concerned with such matters as ecosystem services and substitutability of species, change in ecosystem properties *per* *se* would be the key impact, rather than change in original species composition (except as the latter affected, say, ecosystem services [Ehrlich and Mooney 1983]).

Other sorts of impacts may be of greater concern to the public and policymakers than the above impacts. In particular, many people would see the economic, public health, or aesthetic impact of an NIS as the impact of interest. However, there is no reason to consider these as good measures of impact from a conservation or ecological viewpoint, except as they might correlate with a biologically based measure (e.g., Williamson 1998), such as number of native species affected or extinguished globally or locally. Budget allocations are not always correlated with conservation priorities. For example, allocations to endangered species recovery efforts are not always based on degree of endangerment (Kohm 1991, Foin et al. 1998).

It is important to make any measure of impact operational if it is to be used in prioritizing management efforts. Studies exist that catalog different aspects of invasion impact, such as area covered, number of native species affected, and types of ecosystem process changes, but no effort is made to transform these data into a single number for each species, which would allow comparisons among them (e.g., Schmitz et al. 1997). Thus, there is not an operational metric.

An initial attempt to capture the biologically relevant aspects of impact (Parker et al. 1999) consists of the equation

$$I = R \times A \times E$$

where total impact I of an NIS is the product of range size R, the average abundance A across that range, and the effect E, per unit individual or biomass of the NIS.

Some biological aspects of impact are not subsumed by this equation. For example, effects of gene flow from an NIS to related native species may be important (Rhymer and Simberloff 1996). While R and A must affect the likelihood that and rate at which this phenomenon will occur, it is unlikely that this likelihood and rate can be completely captured in one variable, E. Much would depend on the exact configuration of the occupied area, distribution of abundance of the NIS, and distribution and abundance of the native relative. Nevertheless, the majority of biological impacts can probably be expressed by this equation, although actually measuring its components may be technically difficult or impossible in particular cases.

R and A are straightforward measurements, though not always easily collected. The very fact that lists of areal coverage of a series of NIS are available for some sites (e.g, Schmitz et al. 1997, Clements 1998) suggests that R is often attainable. The distribution of abundance, A, is also a staple of ecological research. For some plants, percent cover is more easily estimated than abundance or biomass and may be an acceptable substitute measure. It may be more difficult, on average, to estimate the distribution of abundance of animals because of their movements, activity cycles, sizes, and other traits. However, a wealth of standard techniques exists for such estimation, if sufficient resources can be mobilized.

The per unit impact, E, is another matter. The full range of effects is often unknown but probably vast, and quantification of even the known effects is sometimes not possible with currently available knowledge and techniques. At least five types of effects, all of which could ultimately affect populations and species, would have to be considered for the equation to be made directly operational (Parker et al. 1999).

So what could or should be measured?

First, NIS may affect individual traits of growth, reproduction, morphology, or behavior of native species. Determining that such effects exist is often a difficult research project, but there is a sufficient corpus of literature on such research that the outlines of how it would have to be conducted are usually clear. One example is a study of the impact of the NIS spotted knapweed (*Centaurea maculosa*) on the native *Arabis fecunda* in Montana (Lesica and Shelly 1996). Impacts of the invader on individual survival, growth, and fecundity of the native were measured. Similarly, in the Gulf of Maine, Petraitis (1989) measured the impact of the non-indigenous periwinkle, *Littorina littorea*, on individual growth and survival of a native limpet, *Notoacmea testudinalis*, while Lohr and West (1992) showed how habitat selection behavior of native brook trout (*Salvelinus fontinalis*) in a North Carolina stream was affected by introduced rainbow trout (*Oncorhynchus mykiss*).

Second, NIS may have numerous genetic effects. As observed above, these may not easily be transformed into a single value E, although there has been insufficient detailed study of such effects to conclude that this exercise is futile. The degree of introgression his been quantified by molecular evidence in several cases. For example, Abernethy (1994) has determined the extent to which individual red deer (*Cervus elaphus*) have received genes of introduced Sika deer (*C. nippon nippon*) in different locations in Great Britain. But it is not clear how to compare this impact with ecological impacts. In addition to hybridization and introgression with native species, NIS can alter selective regimes and/or gene flow of the latter. There has been little search for generalization about the circumstances under which these impacts occur, although experiments on potential impacts of genetically modified organisms on natives provide some data (Bergelson 1994).

Third, an NIS can affect population dynamics and/or density of native species, for example, by consuming or competing with them. The extent to which impacts on population dynamics are correlated with biomass or abundance of the invader in general is unknown; much literature assumes implicitly that the correlation is high. If this were true, at least for this component of impact, E drops out of the equation and A is a sufficient variable. Several studies that assess impacts of an NIS on individuals of a native species go further and demonstrate a population impact. For example, the study of impacts of *Centaurea maculosa* on *Arabis fecunda* cited above also detected changes in population growth rates. In the Azores, Ramos (1996) showed that the non-indigenous trees *Cryptomeria japonica* and *Pittosporum undulatum* depressed the population density of the native bullfinch (*Pyrrhula murina*) below that in native laurel forest. Grosholz and Ruiz (1995) demonstrated that the introduced European green crab (*Carcinus maenas*) had an impact on the density and size distributions of many coastal invertebrate species in central California.

Fourth, the impact of an NIS is often sought at the community level. Thus, for example, native species richness of a community can be changed by an NIS, as can compositional structure (however measured). Bellan et al. (1996) measured the change in native species richness caused by the non-indigenous alga *Caulerpa taxifolia* in the Mediterranean, while Flecker and Townsend (1994) assessed change in insect diversity and total biomass wrought by the introduced brown trout (*Salmo trutta*) in New Zealand. Various indices of community “health” or “integrity” may be affected by an NIS, but the relationship of this change to changes in populations and species has generally not been explored. The value of the natural quality index for prairies (Swink and Wilhelm 1994) depends in part on the presence of NIS; however, the response to NIS is not on a per capita basis. Further development of such indices could provide useful, relatively easily measured indicators for summed impact of an invasive NIS on all native populations. However, research on this point is certainly not adequate.

Fifth, as noted at the outset, an NIS can have effects on ecosystem processes, and it may be convenient to measure those effects directly rather than how they affect native populations on a species-by-species basis. Thus, for example, the amount of nitrogen fixed by X individuals (or Y grams) of an N-fixer may be easier to measure than the changes in the population sizes (and other characteristics) of the resident native species, even though the latter characteristics are what concern us ultimately as impact. Asner and Beatty (1996) measured the effect of the African grass *Melinis minutiflora* on nitrogen dynamics in Hawaiian shrubland and also showed that changes in nitrogent dynamics affected succession. Lacey et al. (1989) showed an impact of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield in Montana. Kourtev et al. (1998) measured changes in pH and other soil properties affected by an interaction between earthworms and the NIS nepalgrass (*Microstegium vimineum*) and Japanese barberry (*Berberis thunbergii*).

Spatial and temporal variation complicates measures of most ecological phenomena. Just as A in the equation would have to be derived from the full distribution of abundance across the range (because abundance varies spatially), so E would vary spatially and temporally. Spatially, because the biotic and abiotic environments of an individual (or unit of biomass) of an NIS vary spatially. For example, Japanese honeysuckle (*Lonicera japonica*) appears innocuous in Indiana Dunes National Park, where it does not reproduce sexually, though it is a scourge in national parks further to the south (R. Hiebert, pers. obs.). Temporal variation is probably even more complex (and perhaps more difficult to capture in a sampling regime because it is not as well understood). Cyclic and other dynamic change at the individual and population level is pervasive, and an NIS can evolve in ways that could effect impacts at various levels. A particular temporal complication is the common phenomenon of a time-lag between the arrival of an NIS at a site and its impact (e.g., Kowarik 1995). Part of this time-lag may be associated with changes in R (range) and abundance (A), but there may also be a lag in E, the per-unit impact. For example, individuals of an NIS might eat more prey and/or different prey species as they age, or the impact of a fire-enhancing plant may take years to be manifested.

A sampling scheme to account for all of this variation would be a very ambitious undertaking; the fact that many kinds of variation are poorly known for many species complicates attempts to produce efficient, stratified sampling regimes. Thus, joint research efforts by managers and academics would have to be undertaken to identify shortcuts, such as PCA (and other multivariate techniques) and bioindicators (Parker et al. 1999). Any proposed bioindicators and multivariate approaches would have to be rigorously field-tested.

Relationship between site management and this approach to measuring NIS impact

By its incorporation of R (range) and A (distribution of abundance), the equation can generate a global measure of impact of each NIS. However, from the standpoint of a manager prioritizing NIS control activities at a particular site, the global impact is probably not highly relevant. There may be moral or legal reasons why the manager of a specific site wants to prioritize activities to minimize regional or global NIS impact, but generally he/she is trying to do what is best for a particular site. Specific site goals may dictate that a manager account for other factors than simply the degrees of impact (or threat) posed by a series of NIS – for example, a wetland site may have a management objective of optimal stopover use by migrating waterfowl. To achieve a current ranking on-site of all NIS present, R and A may be more or less easily estimated on-site, but E would be a formidable task for all the reasons stated previously. Thus, if E has been estimated elsewhere and these estimates were available in an accessible data base, the desired ranking would become more feasible. For a manager, compatibility of units is crucial if he/she is even to begin to apply the above equation. Some guidance will be required in dealing with the various units of density, percent cover, and the forms in which E is tabulated.

Further, if local R and A are small, I = R x A x E will be small, but the manager should be concerned not only about current I but about the probability that the NIS will spread, the probable rate at which it will spread, and the impact it might achieve if it spreads. The manager thus needs access to data gathered elsewhere, both on E (because this metric is so difficult to estimate) and on spread characteristics. And, of course, information is also needed on site characteristics where the data were gathered, to allow assessment of the suitability of using such data to estimate likely trajectories at this particular site. If these data were compiled in an accessible format that allowed comparison of the best information about impacts of each invasive NIS, managers, researchers, and policymakers would have a tool on which to base resource allocations.

A database containing the above information could contain other information relevant to a decision about whether and how to attempt to control an NIS that currently has a low on-site value of I. For example, mutual facilitation among various NIS is sometimes a key component of impact (Simberloff and Von Holle 1999); an increased R x A for one NIS could increase either the probability of success or the degree of impact of other NIS. Or there could be thresholds such that a small population of an NIS is unlikely to grow, whereas a large population is likely to grow still larger very rapidly. And experience with economic costs of control would be relevant to a decision (see below).

In sum, the same sorts of measures that would allow assessments of global impact of an NIS would be necessary both for assessments of site impact and management decisions based on estimated current impact and scenarios of future impact. The difficulty of gathering some of the data crucial in the estimation of such measures dictates that managers have access to a data base that provides them with much of the relevant information.

B. Decision theory

Reliable prediction of a rare event is difficult because of what is known as the base-rate effect (Matthews 1997a; Smith *et al*. 1999). The small number of correct predictions is swamped by the large number of false positives, a phenomenon well known to epidemiologists studying the incidence of rare human diseases and disorders (e.g., Baldessarini et al. 1983). Imagine for a moment attempting to diagnose a disease with an incidence, or base-rate, of 1%. Out of 1000 individuals, there are only 10 who would actually have the disease. Suppose now that we devised a diagnostic system based on the best possible information that had an accuracy of 80% - i.e., it would correctly identify eight of the 10 diseased individuals. While this initially seems useful, if the accuracy were the same for non-diseased individuals, we are misidentifying 20% of the remaining, non-diseased individuals, creating 990 x 20% = 198 false positives. In other words, the system will identify a total of 206 diseased individuals, but only 8 of these (4%) actually have the disease. Now whether this rate of false positives is acceptable depends on the value of a correct diagnosis relative to the damage caused by a mis-diagnosis. If, for example, early diagnosis allows rapid, benign, inexpensive and effective treatment, then we might proceed with treatment for the 206 individuals, despite the knowledge that few of them are actually ill. If on the other hand the only treatments are in themselves very dangerous or costly, we may be better advised to allow time for the disease to develop in the few diseased individuals before embarking on medication. Otherwise we will largely be using our limited health resources to cause physical and economic harm to a large number of healthy people who were in no danger. The conditions under which we can ignore the diagnosis depend on the base-rate of the disease (i.e., how rare it is), the accuracy of our screening process, and the relative costs and benefits of treatment. A body of theory known as decision theory helps us to determine these conditions mathematically and gives us a structured way of making these kinds of decisions. In essence, we can say that, for a given base-rate, the accuracy of the prediction needs to be greater the greater the loss caused by having false positives (Smith *et al*. 1999). Moreover, the rate of false positives (the proportion of cases given higher priority than they in fact need) declines as the base-rate increases.

The importance of this interaction between the base-rate for pests and the accuracy of a prediction procedure has not been well appreciated by invasion biologists. However the analogy between diagnosing and treating a rare illness, and identifying and controlling an invader from the suite of NIS in a natural area, is a good one. Both are subject to the base-rate effect, and both are likely to have undesirable consequences if a misdiagnosis is made. For example, given limited resources, a large expenditure on herbicides to control a naturalized species in a national park might only be worthwhile if

1. we could identify it as part of a group with a generally high base-rate probability of becoming a high-impact invasive (e.g. tropical pasture species in northern Australia; Lonsdale 1994) , or
2. we had a very accurate system of identifying invasives, or
3. if the costs of control (use of park resources, damage to native vegetation, etc) now were small relative to the costs later if the species were to become invasive.

An interesting quirk of this system of analysis is that there may be different accuracy rates for the identification of pests and non-pests. The precise conditions (in terms of base-rate, accuracy, and relative costs) under which we should take action based on a prediction of pest status can be determined mathematically (Matthews *et al*. 1997b; Smith *et al*. 1999). Note that these costs and benefits need not be in monetary terms – they may be expressed in arbitrary units of societal happiness (though it is implicit that the units be the same for the costs and the benefits).

Other fields such as medical science (Baldessarini et al. 1983) and earthquake prediction (Matthews 1997b) have recognised the value of the decision theory approach and made great advances. Invasion biologists may have much to learn from them in this area. In the meantime, there is a developing literature on decision tools (though not strictly on decision theory) for controlling invasive species, and it would seem to us that the limiting factor is less the availability of tools and more the training of managers in their use. A useful overview of existing decision tools for natural resource managers is provided by Hiebert (1997). We recommend that:

1. the application of decision theory to managing NIS be explored with a view to developing testable rules and analytical decision tools for managers;
2. natural resource managers obtain training in the use of existing decision tools for NIS management; and
3. a record be kept of decisions made using these tools and their subsequent outcome, so that there are data to adjust the algorithm, if necessary.

Whatever analytical techniques managers use to make their decisions (see Hiebert 1997), they will be aided enormously by a readily accessible database of up-to-date information such as we describe in the following sections.

A GLOBAL DATABASE

A global database will be useful at the site level because it would make available data from other sites about the potential for serious ecological impacts from an NIS. As discussed above, these data will allow a manager to assign relative weights to the threats from several different species if they all cannot be controlled simultaneously. The database would also be valuable above the site level because, as discussed above, understanding of the global ranges of invasion for species will substantially improve our ability to predict which species are likely to threaten new regions and continents prior to their arrival (Scott and Panetta 1993). The ability to clarify patterns of invasion may allow development of proactive, well-substantiated lists of prohibited species.

For a global database on species invasion rates and impacts in different regions and communities to be useful to conservation site managers, it must contain several types of information (Table 1). An inherent difficulty in this effort is the need to standardize the data on invasiveness to maximize our ability to compare and to prioritize control efforts, while recognizing the temporal and spatial variability in species behavior and in species and community responses to the invader. This variability will require care and explanation in data entry and caution in interpretation. However, these concerns are not different than those associated with the current, limited, and substantially anecdotal information that is now available for management planning. Because of the dynamism of these species and our information on them, all data entered into the database should be associated with a date and attribution.

An additional difficulty in constructing this database is that different species will require different information for development of useful understanding of each species and its potential to threaten natural systems. The fields outlined in Table 1 represent the breadth of data that might be necessary to understand likely impacts of individual species; however, not all the fields need to be populated for each species immediately. Additionally, the precision of the data included will vary by species and field. Source information will assist users in assessing the reliability of the data present. Again, inclusion of the best data available and updating of the database as data quality improves will provide an information resource that far exceeds any source currently available to managers and researchers. Decisions about which fields to populate and the detail necessary will depend on the species involved and its potential impact on natural areas (see below).

Species included in the database should initially be determined from lists of species invasive in natural areas compiled at any scale available (national, regional, management unit).

Such lists have been compiled for many countries, including Australia (e.g., Humphries et al. 1991) and South Africa (Henderson 1995). In the United States, while the Federal Noxious Weed list primarily addresses agricultural weeds, several federal (NPS, USFS) and state agencies have developed lists, as have local Exotic Pest Plant Councils and some managed areas like national parks.

While the potential information available for each species is extensive (Table 1), not all fields need to be populated at once or ever. Description and mapping of the native range is useful for prediction of both potential habitat types and ranges (Rejmánek 1994) in new locations. An overview of the data on area and impacts should be described within the rationale for inclusion. The fields for total area invaded, range of invaded areas, numbers of invasion locations, rates of spread, or degrees of impact within sites should also be filled and used to determine whether the organism is of sufficient threat to natural areas to warrant additional resource allocations for populating remaining fields. Where data do not exist for high priority species, research needs will be clearly indicated by the database.

General categories of modifications to natural systems attributed to invasive NIS have been identified at several scales (MacDonald et al. 1989, Gordon 1998, Mack et al. 1999). Information on broad types of genetic- to ecosystem-level impacts entered into the database (Table 1) may be based on anecdotal information. More specific, quantified impacts should be recorded by region and community type in the next group of fields. These data, combined with those on area invaded and abundance, may be used to calculate an overall likely impact value (I) for a particular community type (Parker et al. 1999).

As discussed above, where overall impacts may be calculated for several species invading a particular management unit, prioritization of which species to control over time may be determined from (I), the likely rate of spread in the community at the management unit, the cost of control, and likely results of that control. Costs and results include considerations of both continued control needs for the invader and any restoration of processes or species necessary following removal of the invader. At a particular location, the full suite of management objectives will determine the priority of controlling particular invasive NIS.

Accessibility of the database on the Internet is necessary if it is to have a truly global scope. This web-based management tool must provide unrestricted access to all interested users. Further success will require careful consideration of design to optimize its usefulness for a range of interests and users from a global community. Clearly, the minimum amount of data that is most useful is that about "invader status" – i.e., simple presence/absence for a list of NIS. However, as the scope and utility of the database expand, the information fields must be able to keep up. It is much easier to remove fields that prove cumbersome or not useful than to add new fields and then to backtrack to update older entries. The fields proposed in Table 1 are purposely broad for this reason. Of course, users may be bewildered by an enormous set of fields while seeking information or by a very long submission form (see next section) when transmitting information. So there will have to be clear ways to focus on just those fields that are relevant to a particular case. Although much of this information is not readily available at other sites that have attempted to act as such a tool, this information is clearly valuable and such a format may encourage the development of such information prior to submission of an NIS for consideration. The very existence of such a database may guide both managers and researchers who are initially without much insight about what to look for and to measure. The use of electronic submission forms is expected to enhance the global scope of the database. Table 2 lists desirable features of a sufficient global database. Additionally, it would be useful to include a Bulletin Board Service built in for each species where managers, researchers, and other users could post comments and questions immediately, without regulation (with the implicit recognition that these are comments, not verified facts).

POPULATING THE GLOBAL DATA BASE

Deciding what fields are needed for NIS in a centralized database is not difficult, although it will differ among groups of organisms. Populating the data fields will be the laborious, time-consuming task. The obvious first step in this task is to mine existing information and data sets. This information exists in museum and herbarium collections, floras and faunas, published documents, internal reports, web sites, data clearing houses, localized unpublished databases, and expert opinion. We reiterate that unpublished information gathered by natural area managers is part of the latter category. Methods to identify and to retrieve this kind of information will have to be developed, as will direct input forms.

There are currently databases, non-indigenous floras, and lists (and these are proliferating) for invasive species in the United States, Canada, Australia, and Great Britain. Most are for vascular plants. Efforts are also underway to develop national and hemispheric databases. For example, the U.S. Federal Committee for the Management of Noxious and Exotic Weeds (FICMNEW) is working to identify and to integrate federal and other programs involved in managing data on non-indigenous plants (Jacono and Boydstuns 1998). Table 3 summarizes relevant existing federal databases on plant NIS (Jacono and Boydstuns 1998). Australia has exotic floras for the entire nation, by state (Humphries et al. 1991). Great Britain has complete records of mammal and vascular plant introductions since the 18th century (M. Williamson, pers. comm.). The United States has noxious weed lists for most states accompanied by distribution maps. However, most states include only species causing major agricultural damage. Exceptions are Florida and Washington, which have more active invasive plant control programs.

Some of the data identified in Table 1 are now available on the Internet. Many existing web sites offer a wide spectrum of information about invasive NIS. Some of these sites are oriented towards educating the general public, while others aspire to provide information to managers who are faced with problems caused by NIS. Along this spectrum there is also a wide range of quality and utility. Some sites have chosen to spotlight a “top five” list of nuisance species, while others attempt to provide information about all NIS within their region of interest.

How much of this information can be used by managers? None of the sites surveyed provided all the information suggested in Table 1. However, a number of sites have stated intentions of becoming web-accessible clearing houses of information for managing NIS. Each site has approached the problems of utility, accuracy, and reliability/standardization somewhat differently from all the others.

The Nonindigenous Aquatic Species Information Resources (<http://nas.er.usgs.gov/>) is one such link. Developed by the Biological Resources Division (BRD) of the U.S. Geological Survey, this site initially focused on the aquatic nuisance species of Florida but has since begun expanding its scope to include North America and beyond. The site provides good public outreach, maps searchable by state and by major hydrological region, links to other information by species and higher taxa, and covers a wide range of organisms.

The Noxious Weeds of North America project (<http://dogwood.itc.nrcs.usda.gov:90/weeds/>) is a cooperative effort between the U.S. Department of Agriculture- Natural Resources Conservation Service and the U.S. Geological Survey – Biological Resources Division. This is a prototype site, the goal of which is to provide information about noxious weeds infesting North America to landowners, resource managers, and the general public. The current site provides information about distribution, biology, and control strategy for two invasive weeds. The site is well-structured, enhanced by a good bibliography for both species as well as other links of interest, and is searchable by region and species, and is likely to be expanded to more species.

Mining and entry of existing data will be a labor-intensive task requiring special attention to quality control. However, the result should be a solid beginning towards a scientific basis for global, continental, state or province, and site-specific NIS management. The Internet may serve as a useful information resource for use in compiling the initial database. The inclusion of graphics and maps is equally important for this global database (see linked material, Table 1). Visual representation of spread, created from local surveys, would facilitate identification of any leading edge to alert managers, or, on a large scale, can represent patterns of biogeographic suitability of sites vulnerable to invaders. GIS technology is an invaluable tool for identification of invasion sites. Relative invasion/exposure potential may be extrapolated from GIS maps displaying sites adjacent to areas already invaded or those close to such areas or along known invasion corridors. Interactive maps also allow for regional searches. In addition to maps, photographs, drawings, and close-ups of important life-history stages that might aid in early NIS identification are an essential part of the global database.

This web-based management tool must provide unrestricted access to all interested users. Further success will require careful consideration of design to optimize its utility for a range of interests and users from a global community. The site must provide multiple forms of access (i.e., search types) as well as standardized searchable fields. Methods and protocols will need to be developed to enter data on species not already in the database and for updating and filling gaps on species already listed. Users will need a format for proposing new species and new information.

From surveys of existing web sites we can learn not only what information is available and what is needed, but also what approaches work well for providing information to a broad group of people who want to know more about NIS. We also need to provide this information without losing site of our primary goal – to provide managers with a decision-making tool. Hence the need for this information to be in one place, a global database. The database need not all be maintained in one place, but the format, procedures, and data collected will have to be consistent for the database to be optimally useful.

CONCLUSION

There are currently a number of databases proposed or initiated by various agencies, organizations, and individuals (e.g, those listed in Table 2 and in Jacono and Boydstun [1998]). Some of these databases are currently limiting the taxa recorded; they have slightly different goals and each aims to include somewhat different information from the others. We suggest that these efforts should be coordinated, standardized, and made more comprehensive. While different entities could easily be responsible for the data on different groups of species (see above), coordination is necessary to ensure consistency in fields and avoidance of overlap. Any database to be developed should include fields that allow better evaluation of biological impacts so that conservation land managers can most effectively order their use of limited resources and time. If this goal is overly ambitious at this time, a database containing only an up-to-date list of invasive NIS everywhere would provide a manager with a valuable tool for a comparatively small outlay. Training in analytical decision-making would enable them to use it most efficiently.

One advantage of access to data on particular species collected by other managers and researchers in other places is that, if a manager is uncertain about what type of impact to assess, he or she can examine and perhaps implement (as appropriate) the procedures that others have followed. This feedback should both increase confidence in the ability to measure a meaningful impact and increase consistency in the available data. As more comparable data accumulate, our ability to generalize and perhaps to identify larger patterns among impact and management approaches will increase (Parker et al. 1999, Smith et al., in prep.)

This database would also provide a wealth of information to address broader questions in invasion biology, many with applied implications for natural area management (Smith et al., in prep.). Thus, the long-term value of the database and website will depend on accessibility to a broad spectrum of potential users. The complexity of ecological, conservation, and management implications associated with biological invasions necessitates close collaboration between the land management and research communities and may serve as a model for similar collaborative efforts.

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Table 1. Fields to be included in a standardized, global database on species non-indigenous and invasive in some regions. For each field, name of person submitting information and date of entry will be required.

- Order/Family
- Latin name
- Common name (languages?)
- Native range (scale is range-dependent)
- Rationale for inclusion in database (presence on an invasive species list [identify if list has statuatory authority], regions invaded with dates, nature of the impact, risk assessment, evidence for causing extirpation of species of concern, etc.)
- Entry pathway and modes of dispersal (e.g., accidental contaminant likely to be re-introduced locally or regionally with further shipments of a particular product or piece of equipment)
- Likely types of impacts with references: (a) geomorphological; (b) biogeochemical (e.g., N-fixer); (c) hydrological; (d) disturbance regime; (e) community structure; (f) community composition / recruitment of natives; (g) local resource availability; (h) one-on-one population interactions (e.g., predation, competition, parasitism, herbivory); (i) facilitation of invasion or other interation with other NIS; (j) genetic (e.g., hybridization with native)
- Biology of the invader: (a) growth form; (b) life history; (c) breeding system; (d) dispersal mechanisms; (e) possible inter-fertile related species; (f) prey or host; (g) toxicity or allelopathy
- By region invaded and community type, what is known about the:

    1. Impacts: (a) area invaded [R]; (b) abundance (in the same units as (c)) [A]; (c) impact (per individual where possible) [E]; (d) ecological impact [I] = R x A x E; (e) rate of spread

2. Control: (a) control methods; (b) difficulty of control; (c) necessity of control (species may invade only early seral stages, low evidence of significant ecological impact, species desirable despite ecological impact, etc.); (d) control costs per unit area
3. (a) Risks or likely consequences of control (e.g., seedbank, site changes subsequent to removal, release of other undesirable species; non-target impacts, including potential interaction of biocontrol agent with natives)

   (b) Risks or consequences of not controlling
4. Restoration requirements and costs (substrate management, planting, etc.)

- Bibliography/experts

Linked material: (a) map of distribution in and beyond native range with climate zones delineated; (b) photograph or illustration and distinguishing characters

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Table 2. Desirable features of a global database, with exemplary existing databases[1].

Electronic submission forms (NAS)

Searchable, standardized fields (HEAR)

Start big (easier to remove than to add fields)

Strong GIS component (USDA, NAS)

Bibliography (USDA)

Multiple means of inquiry (USDA)

Dedicated web-support staff

Peer-reviewed site/review board for anecdotal information (NAS, SGNIS)

Accessible, informative to more than just managers (NBII, NAS, CAN)

http links to additional information (NAS, USDA)

Good photographs or other illustrations (USDA, SGNIS)

Files can be downloaded for extended searches (CAN)

Relational database vs. traditional http protocols (Java solution?) (HEAR/Bishop Museum)

[1] List of acronyms and websites. NAS = Nonindigenous Aquatic Species Information Resources, <http://nas.er.usgs.gov>; HEAR = Hawaii Ecosystems at Risk, <http://www.hear.org>; USDA = U.S. Department of Agriculture, <http://dogwood.itc.nrcs.usda.gov:90/weeds>; SGNIS = Sea Grant Non-Indigenous Species Site, <http://www.ansc.purdue.edu/signis>; NBII = National Biological Information Infrastructure, <http://www.nbii.gov/invasive/index.html>; CAN = Invasive Plants of Canada, <http://www.rbg.ca/cbcn/en/library/invade>.

Table 3. Existing U.S. federal databases with non-indigenous plant information (from Jacono and Boydstun 1998).

Agency	Database	Coverage
Department of Defense	Army Lands Inventory	Noxious species
National Park Service	National Resources Management and Assessment Program	All plants
U.S.D.A. Forest Service	Forest Service Noxious/Invasive Database	All plants
U.S.D.A. Forest Service	Forest Health Monitoring Program	All plants
U.S.D.A. Animal and Plant Health Inspection Service	National Agricultural Pest Information System	All plants
U.S.D.A. National Resources Conservation Service	The Plants Database	All plants
U.S. Geological Survey, Biological Resources Division	Alien Species Databases of the Hawaiian Ecosystems at Risk Project	All plants
U.S. Geological Survey, Biological Resources Division	Nonindigenous Aquatic Species Program	All plant NIS
U.S. Geological Survey, Biological Resources Division	The Exotics Map Database	Invasive NIS