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Risk Analysis for Biological Hazards: What We Need to Know about Invasive Species

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Risk analysis for biological invasions is similar to other types of natural and human hazards. For example, risk analysis for chemical spills requires the evaluation of basic information on where a spill occurs; exposure level and toxicity of the chemical agent; knowledge of the physical processes involved in its rate and direction of spread; and potential impacts to the environment, economy, and human health relative to containment costs. Unlike typical chemical spills, biological invasions can have long lag times from introduction and establishment to successful invasion, they reproduce, and they can spread rapidly by physical and biological processes. We use a risk analysis framework to suggest a general strategy for risk analysis for invasive species and invaded habitats. It requires: (1) problem formation (scoping the problem, defining assessment endpoints); (2) analysis (information on species traits, matching species traits to suitable habitats, estimating exposure, surveys of current distribution and abundance); (3) risk characterization (understanding of data completeness, estimates of the "potential" distribution and abundance; estimates of the potential rate of spread; and probable risks, impacts, and costs); and (4) risk management (containment potential, costs, and opportunity costs; legal mandates and social considerations and information science and technology needs).

KEY WORDS: Nonnative species; potential species distributions; risk assessment; risk management

1. INTRODUCTION

Risk analysis has long been used for the assessment of human health risks associated with chemical contaminants and other hazards (National Academy of Sciences, 1983). Humans were the target species of concern. Assessments were typically restricted to hazard identification, dose-response assessments, exposure assessments, and human health risk characterization. Risk assessment also has been used to quantify the consequences of contaminants, such as the pesticide DDT, on a variety of bird species (Ratcliff, 1967).

While the number of target species has increased over the years, so has the number of contaminants, threats, and stressors under consideration. Target species, in addition to humans and charismatic animal species, expanded to include threatened and endangered species and other plant and animal species. The stressors have grown to include climate change, genetically modified organisms, disturbance, and natural disasters such as earthquakes, floods, and wildfires.

In the 1990s, the basic concepts of risk analysis were used more frequently in the assessments of ecological risks, greatly increasing the complexity of data requirements for complete and accurate risk analyses. For example, Lipton *et al.* (1993, p. 3) suggest that information is needed on "the biotic components and organization of the system, as well

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as assessing the distribution of the stressor within biotic components" including "risk cascades" and "biological, ecological, and societal relevance." Despite these general, well-recognized needs, specific strategies, methods, and the costs and difficulty of acquiring detailed information on all relevant ecosystem components and processes relative to complex stressors such as multiple air or water pollutants, or climate change, continue to be a challenge (Burgman *et al.*, 1993).

We adapted a framework for ecological risk analysis developed by the U.S. Environmental Protection Agency (1992) for broad use in the management of harmful invasive species. The steps include problem formation, analysis, risk characterization, and risk management.

2. PROBLEM FORMATION

The first step in problem formation is scoping the severity of the issue—and the challenges of typical risk analyses are about to take another astronomical leap as consideration extends to invasive nonnative organisms. There are thousands of species of plants, animals, and diseases that have invaded the United States from other continents—species that cause harm to the environment, our economy, and to human health (Mack *et al.*, 2000). Notorious examples include zebra mussels, cheatgrass, West Nile virus, the brown treesnake, plague, kudzu, salt cedar, yellow star thistle, sudden oak death, hydrilla, Dutch elm disease, and nutria, to name a few. No county in the United States is free of invasive species, and more are arriving every week (see www.invasivespecies.gov).

One facet of problem formation is clearly defining an assessment endpoint, that is, the environmental value that is to be protected (USEPA, 1992). In predominantly natural areas, the assessment endpoint might include natural assemblages of native genotypes, species, populations, and ecosystems, and the natural processes that created and maintained them. Thus, harmful invasive species that might drastically reduce or replace native taxa, negatively impact ecosystem components or processes, or negatively affect human health serve as a significant external threat to the assessment endpoint.

The tremendous challenge ahead of us is in the initial documenting, mapping, and predicting the establishment and spread of invasive species (Chong *et al.*, 2001; Schnase *et al.*, 2002b). Imagine the often difficult case of predicting generally large chemical spills, collecting basic information on where a spill occurred, the toxicity and amount of the chemical, knowledge of physical dispersion processes involved in the rate and direction of spread, and the potential impacts of the costs to the environment, economy, and human health relative to containment costs. Now, imagine the difficulties in detecting the initial establishment of tiny, often cryptic organisms that can have long lag times from introduction and establishment to successful invasion, they reproduce, and they can spread rapidly by physical and biological processes, and by leap-frog like reintroductions by human transportation and trade. Many species that arrive in the United States are intentionally introduced (via seed trade, horticulture, the pet trade, etc.), but many species are introduced unintentionally as "hitchhikers" (i.e., pathogens, ballast water species). The intentional introduction of harmful species remains a potential threat. What do we need to know to understand, estimate, and predict the risks associated with invasive biological organisms?

3. ANALYSIS

Risk analysis for biological organisms requires information on the invading species, vulnerability of habitats to invasion, modeled information on current and potential distributions, and the costs associated with containing (or failing to contain) harmful species (Table I).

3.1. Information on Species Traits

Some species are better invaders than others, and classifying potentially harmful species is a difficult

Table I. Generalized Steps in Risk Analysis and Specific Information Needed for Risk Analysis for Invasive Species

Problem Formation
Scoping the problem
Defining assessment endpoints
Analysis
Information on species traits
Matching species traits to suitable habitats
Estimating exposure
Surveys of current distribution and abundance
Risk Characterization
Understanding of data completeness
Estimates of the "potential" distribution and abundance
Estimates of the potential rate of spread
Probable risks, impacts, and costs
Risk Management
Containment potential, costs, and opportunity costs
Legal mandates and social considerations
Information science and technology needs

task in risk assessment of biological hazards. Plant biologists have long tried to identify an "ideal" invader species based on traits of successfully colonizing species (Baker, 1965; Bazzaz, 1986; Roy, 1990; Thompson *et al*., 1995). Many traits (Baker, 1965; Lodge, 1993) and strategies (Grime, 1974; Newsome & Noble, 1986) are associated with invasion potential (Table II), but an exclusive set of invader traits has not emerged (Crawley, 1987; Newsome & Noble, 1986; Roy, 1990). This has hampered the ability to predict responses of individual species (Hobbs & Humphries, 1995; Lee, 2001; Reichard & Hamilton, 1997).

Studies that have focused on particular species in selected regions have had more predictive success. Sometimes, a species' life history traits are important determinants of invasion potential (Rejmánek, 1996; Rejmánek & Richardson, 1996; Reichard & Hamilton, 1997). Sometimes, species, taxonomic, and behavioral traits help identify and rank invaders (Lee, 2001; Panetta & Mitchell, 1991).

Obscure species traits may be particularly important for some invaders. European wild oats have awns that self-bury, allowing greater resilience to wildfire with a plentiful seed bank. Plant pathogens such as white pine blister rust had the plasticity to find alternate hosts and target species after arrival in the United States in the early 1900s. There are exceptions to the generalizations in Table II. Not all invaders have all the successful traits, and some species have many of the successful traits, but are not yet good invaders.

3.2. Matching Species Traits to Suitable Habitats

Invasion also depends on environmental characteristics that may predispose a habitat to invasion (Fox & Fox, 1986; Hobbs & Huenneke, 1992; Lee, 2001; Panetta & Mitchell, 1991; Robinson *et al*., 1995; Tyser, 1992). Generalizations of habitat vulnerability to invasion have also been slow to emerge (Lodge, 1993; Lonsdale, 1999; Stohlgren *et al.*, 1998, 1999a, 1999b; Usher, 1988).

The quantity and quality of available resources may be important in assessing the vulnerability of an ecosystem to invasion. In some cases, an invading species may take advantage of underused resources in an ecosystem. For example, *Bromus tectorum* (cheatgrass) in some regions benefits from early spring precipitation, while many native perennial plant species are senescent, or lag behind in growth rates. In addition, cheatgrass can sequester resources faster than slower growing native perennial bunch grasses in postburn areas, further demonstrating that temporal changes in resource availability may be very important to invasion success (Davis *et al.*, 2000).

Thus, identifying invasive species hazards requires an understanding of the receptor ecosystem (genotypes, species, populations, resource availability, and disturbance regime), and information on the invading species' traits (Table II). Invasion is possible only when a vulnerable habitat meets with a species whose traits allow for establishment, growth, and spread (although lag times between introduction and spread are common; Mack *et al*., 2000).

Climate and habitat matching by nonindigenous species may play important roles in the invasion process (Chicoine *et al*., 1985; Panetta & Mitchell, 1991; Venevski & Veneskaia, 2003). Climate matching requires knowledge of the climatic conditions in the original home range of the nonindigenous species and the abundance and distribution of the species (or genotypes) throughout its range. However, many nonindigenous plant species are found in higher and lower latitudes than species in their home ranges, suggesting a possibility of an expanded range in the receptor country (Rejmánek, 1999). This may be due to many interacting forces (reduced competition, predators, or pathogens) in the receptor country, greater dispersal (perhaps aided by more wind or birds),

Table II. Some General Traits of Successful Invaders Adapted and Summarized from the Studies Cited Above

1. Exceptional dispersal characteristics (e.g., by wing, water, animals, zoospores, pelagic stages, etc.; example: wind-blown seed of dandelions, many bird species carrying West Nile virus; Baker, 1965; Lee, 2001; Lodge, 1993).
2. Rapid establishment and growth to reproductive age (example: annual grasses in California, New Zealand mud snail; Newsome & Noble, 1986).
3. Few natural enemies or predators in the new environment (example: mongoose in Hawaii, brown tree snake in Guam; Mack *et al*., 2000).
4. Ability to sequester underused resources (example: shade tolerant Japanese honeysuckle, zebra mussels; Williamson & Fitter, 1996).
5. Copious reproduction (examples: all organisms mentioned above; Rejmánek & Pitcairn, 2002).

Table III. Habitats that Are Typically Vulnerable to Invasion

Tropical island habitats (temperate, subarctic, and arctic islands are typically less invaded in that order; Lonsdale, 1999).
Habitats high in native species diversity such as lowlands close to the coast, riparian zones and estuaries, and terrestrial and aquatic habitats high in light, nutrients, water, and warm temperatures (Robinson *et al*., 1995; Stohlgren *et al*., 1997, 1999a, 2003, 2005, 2006).
Disturbed habitats (e.g., burned areas, plowed fields) and corridors (roads, stream channels, landslides; DeFerrari & Naimen,1994; Fox & Fox, 1986; Hobbs & Huenneke, 1992; Stohlgren *et al*., 1998).
Habitats near heavily invaded sites (i.e., high sources of propagules, source populations; Lodge, 1993).
Areas with high levels of trade and transportation of invasive species (ports, commercial interests that sell plants, animals, seeds, bait, or containers or materials that harbor invasive organisms; Lodge, 1993; Mack *et al*., 2000).

or different levels of disturbance (Burke & Grime, 1996; Fox & Fox, 1986; Hobbs & Huenneke, 1992) or flooding (DeFerrari & Naimen, 1994; Planty-Tabacchi *et al*., 1996).

Predicting whether a habitat is vulnerable to invasion is especially challenging in natural ecosystems since the interactions of many species and ecosystem process are poorly understood. Habitats are usually classified and mapped based on a few dominant species, regional climate factors, or a few environmental gradients (e.g., precipitation, temperature, water depth, or pH), so we have little knowledge of the distributions and abundance of most species that respond to microhabitats that may span several coarse-scale vegetation classifications. Still, some general patterns are beginning to emerge (Table III). Habitats high in native species richness often have high nonnative species richness (Stohlgren *et al*., 1997, 1999a, 2003). Similarly, productive habitats with high light, high nutrients, high moisture, and moderate temperatures tend to have high nonnative species richness (Stohlgren *et al*., 2005, 2006).

Matching species traits (Table II) to microenvironments over large areas of potential invasion will not be easy. Wainger and King (2001) found that only two of the 13 invasion assessment methods incorporated species traits *and* habitat characteristics into the decision analysis. Perhaps because many species possess some or all invasive traits (Table II), many ecologists are focusing on a habitat approach to understand invasion patterns (Davis *et al*., 2000; Hobbs & Humphries, 1995; Lonsdale, 1999; Panetta & Mitchell, 1991; Stohlgren *et al*., 2002; Williamson & Fitter, 1996).

A significant challenge in risk assessments of biological hazards will be quantifying, mapping, and predicting the interaction of species traits and habitat characteristics that promote successful invasion (Lee, 2001). The invasion process may be as "individualistic" (Crawley, 1987; Hobbs & Humphries, 1995) as the species themselves or the habitats they invade. There may be species-specific "invasion windows" in time and space (Johnstone, 1986; Mack *et al*., 2000).

3.3. Estimating Exposure

Even after an "invasion window" opens, exposure assessments will be difficult for moving organisms because they can reproduce and sometimes spread quickly. West Nile virus took only four years to spread across the United States after it was found in 1999 (http://westnilemaps.usgs.gov/2004/historical.html). General pathways may be clearly identified, but very poorly quantified. For example, many aquatic organisms have arrived in estuaries, rivers, and lakes from ballast water, with small organisms (larvae, eggs, pelagic stages, etc.) being stored in the ships' home port before transportation and release in a receptor port (Lodge, 1993). Still, even rough estimates of the abundance, viability, and condition of arriving organisms are unknown—for invasive or less-invasive species. Similarly, small seeds of nonnative annual weeds contaminate native forage and crops. It is very costly to examine and purify every large bag of seeds. Shipping manifests rarely describe organic hitchhikers in sufficient detail to accurately assess exposure.

The concept of "propagule pressure"—the number and viability of reproductive units arriving at a given habitat—may determine invasion success (Lodge, 1993). However, many invasive species do not have large, obvious, easily counted propagules, and quantifying propagule pressure over large areas is problematic. Many pathways and corridors to invasion are poorly understood. Corridors may include the matrix of roads and riparian zones that may facilitate the spread of invasive riparian plants such as purple loosestrife and tamarisk. Railroads are linear, disturbed habitats of invasion for many nonnative plants species. How many seeds, spores, and pelagic stages arrive in the United States undetected? How many propagules land in each habitat? As difficult as this task seems, some estimates are possible for some species (based on trade and transportation volumes and patterns, surveys, and rudimentary models). We need more "practice" estimating exposure.

3.4. Surveys of Current Distribution and Abundance

Surveying for the early invasion of harmful species is made difficult by small population size, patchy distributions, and the cryptic nature of many initially rare species in complex landscapes and waterways. Cost is a major consideration because only a small percentage of any area can be affordably surveyed. Reductions in funding typically restrict not only the number of survey points, but also the pattern and completeness of sampling at each point. Completely random or unbiased survey techniques may be unlikely to detect new cryptic invaders, especially if costs constrain sampling intensity and completeness. However, subjective sampling for invasive species has typically resulted in an overrepresentation of records in flat spots, along roads, and near cities with universities (Crosier & Stohlgren, 2004).

One of the preliminary steps in risk analysis is augmenting initial opportunist or subjective survey information with more systematic, less biased, and more comprehensive surveys in an iterative approach (Fig. 1). This is termed an exposure evaluation (USEPA, 1992). In the initial phase, only a few established individuals or populations are known to investigators. They may add a few other observations nearby in similar or different habitats to get a conceptual, first-approximation model of the species' distribution and abundance. Upon the initial sightings, the proper authorities are alerted for rapid response control measures and restoration (although, at present, these efforts are lacking or uncoordinated in most areas, and for most species). Species' affinities to habitat types are noted, as are information gaps such as unsurveyed habitat types or areas.

The second phase of surveys integrates unbiased stratified random sampling with gradient sampling designs for robust spatial statistical models (Fig. 1). This provides much needed information on the probability of occurrence in different habitat types, and preliminary information on the environmental tolerances of the target species. Note that the actual current and potential distributions of a species are very difficult to determine from limited surveys (see below)—but it is a start. Statistical and spatial interpolation models

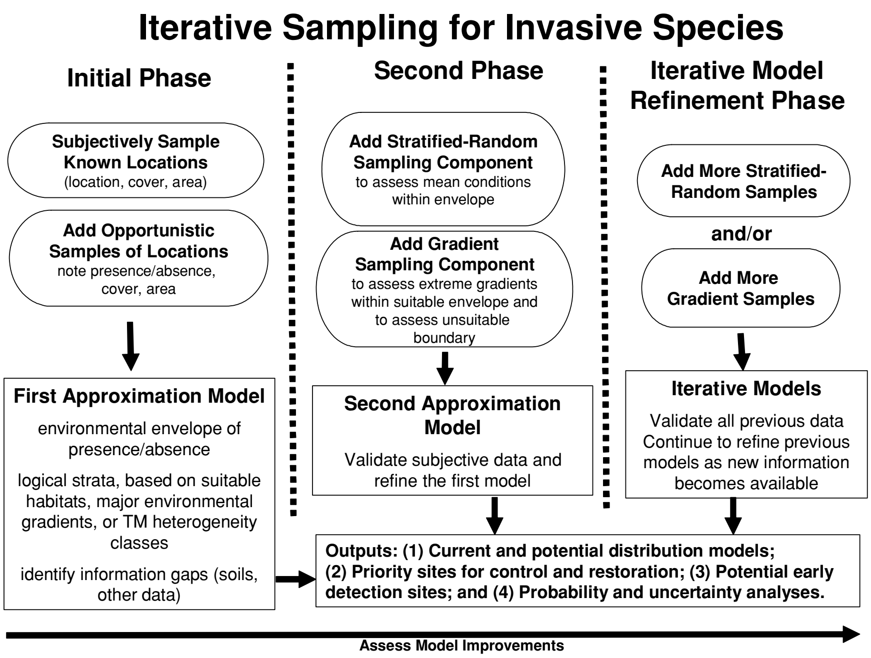

Fig. 1. An iterative sampling approach for documenting, mapping, and predicting the abundance, distribution, and spread of invasive species.

based on stratified random and gradient analysis techniques allow for a second approximation of species distribution and abundances. New survey data from opportunistic sampling, stratified random sampling, and gradient sampling further improve and validate the distribution maps over time. Since species migrate, adapt, hybridize, expand, and contract in population size, risk analysis surveys for invasive species must be an iterative and ongoing process (Fig. 1).

4. RISK CHARACTERIZATION

Risk characterization includes understanding of data completeness, estimating the "potential" distribution and abundance of invasive species, estimating the potential rate of spread of species, and estimating their probable risks, impacts, and costs.

4.1. Understanding of Data Completeness

A critical feature of risk characterization for invasive species is an understanding of the taxonomic, geographic, and temporal completeness of data in the region of concern (Fig. 2). Most biotic inventories in natural areas are woefully incomplete (Stohlgren *et al.*, 1995), and mapped distributions of invasive species mean very little without some understanding of data completeness.

A given area in a large landscape or region may have any combination of completeness (Fig. 2). Only a small portion of the area might have been surveyed (low geographic completeness), it may have been surveyed only once (low temporal completeness), and only one or a few species or genotypes might have been surveyed (low taxonomic completeness). This might be termed a poorly surveyed site. Conversely, the entire area might have been well surveyed (high geographic completeness), it may have been surveyed many times (high temporal completeness), and most species or genotypes might have been surveyed (high taxonomic completeness).

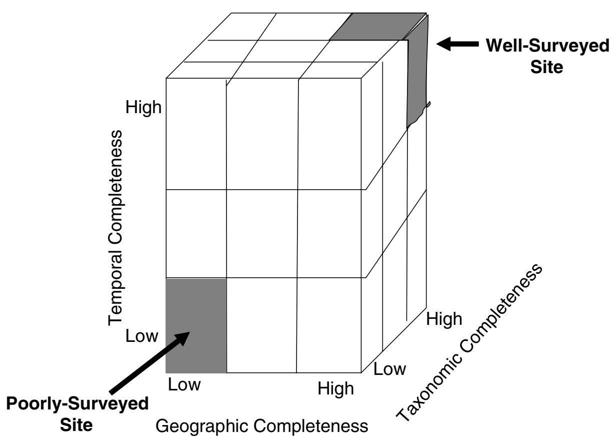

Fig. 2. Schematic of geographic, taxonomic, and temporal completeness of data.

It would be very helpful if maps of the distribution or abundance of invasive species could be accompanied by information on the various levels of completeness throughout the study area. Then, land managers would understand the limitations of the maps, and be able to set priorities for future surveys and for early detections and rapid response efforts. Maps of invasive species or other biological hazards that have explicitly quantified and conveyed information on data completeness are rare. This must become commonplace in risk analysis.

4.2. Estimates of the "Potential" Distribution and Abundance

Why is understanding potential distributions so important? The large number of nonnative species, combined with initially small population sizes, makes projecting potential distribution and abundance very important. Two nonnative ant species might have similarly small populations, but one of the species may have enormous tolerance for a range of temperature, moisture, nutrient, and disturbance regimes, thus having a greater potential distribution. Setting priorities among species requires accurate estimates of the future distribution and abundance of species. Estimating the potential distribution and abundance of an invasive species requires the information needs outlined above (Table I; needs 1–5), integrated with remote sensing and fairly sophisticated mathematical models. A species' potential distribution is similar to a habitat suitability model where abiotic and biotic factors are carefully quantified relative to the plasticity and adaptive potential of the target species and genotypes. Patterns of habitat invisibility have been slow to come, let alone mechanisms explaining these patterns (Mack *et al.*, 2000), and the complexity of this task should not be underestimated. There are a growing number of habitat models for invasive species based on a few climate, topographic, or soil variables (Chong *et al.*, 2001; Schnase *et al.*, 2002b; Venevski & Veneskaia, 2003, see www.invasivespecies.gov). Their singular objective is to describe the entire range of possible occurrences of species.

Current "potential distribution" models have several limitations. They are based on only a few predictive factors and are affected by the scale, resolution, and accuracy of spatial data inputs. The models do not include information on more than one biological species (the target organism), so they do not include the complex of interspecies interactions (e.g., competition, herbivory, predation). The environmental factors in the models are all held constant, and the local disturbances (e.g., fires, floods) and processes such as grazing and mortality of competing species are generally presumed constant, which is rarely or never the case. Species-habitat relationships and species mapping (except for humans) are in their infancy. Yet, developing these capabilities is paramount to the next difficult challenge in risk assessments of invasive organisms—predicting rates of spread of invasive species.

4.3. Estimates of the Potential Rate of Spread

After mapping the potential distribution of a species, mathematical models predicting the spread of a invasive species are essential (Chong *et al*., 2001; Schnase *et al*., 2002b). Land managers may want to set priorities for control based partly on the area of potential habitat, the effects of the species throughout its range, and the rate at which the species could spread from its current distribution to its full potential distribution. There are many models being explored for predicting rates of spread from simple dispersion or deterministic spatial models to stochastic models (see Hastings *et al*., 2005 for review).

Spread models have more limitations of potential distribution models. Even simple dispersion models of species spread may be heavily dependent on complete information on the distribution and abundance of the target species, and the predictions of the establishment, growth, reproduction, and migration of meta-populations in complex environments.

Moderately sessile organisms such as plants might provide simple cases to begin developing estimates of species spread. There may be a link between establishment success and invasion success for many species. For example, in the Central Grasslands and Rocky Mountains, nonnative species richness and cover in habitats are positively associated with high native species richness, high soil fertility, and high light availability (Stohlgren *et al*., 1997, 1998, 1999a). Yet, accurate monitoring of the distribution, abundance, and spread of meta-populations, species, and genotypes remain rare in the ecological literature (e.g., Harrison, 1991).

4.4. Probable Risks, Impacts, and Costs

The costs associated with invading species may be environmental, economic, or costs to human health. Assessing environmental risks includes potential costs to native species, populations, and genotypes, as well as costs to ecosystems components and processes (i.e., the assessment endpoints). The secondary concern to species, populations, and genotypes is the rapid mortality, loss of abundance, and loss of viable populations such as the effects of Dutch elm disease on elm trees or the loss of native populations of *Phragmites* due to invasive nonnative genotypes of same species. About 42% of the species listed on the threatened and endangered species list (plants and animals) are listed because of threats from nonnative species (Wilcove *et al*., 1998). The primary concern to species is, of course, extinction, exemplified by the loss of 12 native species of birds in Guam due to the voracious invasion of brown treesnake (Fritts & Rodda, 1998). Quantifying reductions in native species, loss of native genetic diversity, and extinctions requires nonmarket valuations.

Invasive species can have indirect effects by degrading habitat quality for native species, affecting nutrient cycling, and promoting disturbances such as wildfire (Mack *et al*., 2000). These impacts may be slow and chronic, such as the salinization of soils invaded by salt cedar, or they may be cataclysmic such as the rapid spread of aquatic weeds in the southeastern United States and the spread of sudden oak death in California.

The economic risks of invasive species were brought to our attention by Pimentel *et al*. (2005), who estimated annual "costs" to the United States to be in excess of $120 billion/year in lost agricultural production, expenditures for control, human health costs, and other losses. However, we often lack site-specific costs and valuations for individual species. Dr. Pimentel could roughly estimate the costs of control for Norway rats in New York City, but detailed costs for the thousands of invasive species in the United States are not easily tabulated—partly because we have poor maps of the distribution and abundance of species, much less damage estimates throughout their ranges.

Invasive species can directly and indirectly affect human health. Direct affects are seen by the over 250 human deaths due to West Nile virus in the United

States since it arrived in 1999, and several deaths resulting from plague, killer bees, fire ants, and other invaders. Indirect effects on human health include secondary effects of pesticides, herbicides, and allergic reactions, bites, and unknown long-term effects from, say, coating the skin with harsh chemicals to avoid mosquito bites and West Nile virus.

5. RISK MANAGEMENT

Risk management includes evaluating the containment potential, costs, and opportunity costs related to invasive species containment; legal mandates and social considerations for controlling various species; and commandeering information science and technology needs.

5.1. Containment Potential, Costs, and Opportunity Costs

Risk management begins with selecting priority species to control, which, in turn, depends on the potential effectiveness of control and restoration efforts relative to costs. Some species are more difficult to contain than others. Cheatgrass is widespread in many states, but there are no cost-efficient techniques for manual, chemical, or biological control over large areas, and the threat of reinvasion is high after fire. There are readily available biological control agents for several nonnative thistles, but thistles can persist in small populations and scattered individuals to repopulate control areas later. The effects of control agents on nontarget species must also be considered. Still, containment potential, relative to costs and potential for long-term success, are important considerations when setting priorities for control (see http://www.usgs.nau.edu/swepic/aprs/ranking.html).

Risk management also requires resource managers to select priority habitats for control and restoration activities since most ecosystems contain at least some nonnative species. Thus, managing risk depends on selecting the highest priority species and habitats in a triage. The invasion may be just beginning in many areas, so early detection and rapid response capabilities must be conducted with a similar triage approach.

Opportunity costs also should be considered—if you choose to spend time and effort on containing widespread Species A, will Species B, C, and D take the opportunity to expand unchecked? Conversely, attacking Species B, C, and D while their populations are small may be more cost efficient in the long run compared to Species A. Obviously, such decisions would benefit from predictive modeling of potential rates of spread linked to environmental, economic, and human health costs. Without the models and the linked data sets, our ability in selecting priority species for control is limited. We also need to integrate economic analyses to better quantify impacts of invading species.

5.2. Legal Mandates and Social Considerations

Certain priorities for the control of invasive species will be based on legal mandates, county regulations, and a sense of "urgency" based on other social considerations regardless of the collective invasive species threats to the ecological endpoints. For example, some states and counties are legally bound to address weeds classified as "noxious" (often poisonous) regardless of the abundance, spread potential, and other impacts of other weeds in the area.

Other social considerations include harmful human pests (e.g., fire ants, killer bees, West Nile virus) or threats to listed as threatened or endangered species or habitats, private property rights, or unfairly distributed economic costs for control. In any case, legal mandates and social considerations must be considered when setting priorities for control.

5.3. Information Science and Technology Needs

The challenge of risk analysis for invasive species is compounded by the demanding requirements it places on information science and technology. For example, in the risk analysis strategy described above, the first steps of assembling information about the biology, ecology, and natural history of a species along with associated habitat characteristics are themselves nontrivial information management problems. The accumulated volume of biological information and data collected over the past 250 years is massive and increases steadily as large-scale digitization and database efforts bring more and more information online. Humans still play a crucial role in the processing and assembly of this type of information, which is often not as amenable to automatic correlation, analysis, synthesis, and presentation as many other types of information. People act as sophisticated filters and query processors—locating resources on the Internet, downloading data sets, reformatting and organizing data for input into analysis tools, then reformatting again to visualize results. This process of creating higher-order understanding from dispersed data sets is a fundamental intellectual process in any strategy for risk analysis, but it breaks down quickly as the volume and dimensionality of the data increase (Schnase *et al*., 2003).

The challenge of understanding taxonomic, geographic, and temporal completeness of data in a region of concern translates into a requirement to systematically catalog "meta" knowledge about the information used in analyses. These meta-data are a crucial aspect of all scientific databases, and in the United States, the National Biological Information Infrastructure (NBII) has taken a lead role in establishing documentation standards for biological information and provides tools to make this often burdensome task more palatable and a customary part of scientific publishing. However, refinements of meta-data standards to invasive species risk analysis in an important emerging need (Schnase *et al.*, 2003).

In risk analysis for invasive species, estimates of the potential distribution and abundance of an invasive imply an unprecedented level of integration of landscape scale, space-based measurements, and the development and validation of new remote sensing data products. To be of practical use, the application of many geostatistical modeling approaches at landscape and continental scales requires the use of high-performance computing, which often means developing new algorithms capable of exploiting commodity cluster computers (Pedelty *et al*., 2003). Our ability to estimate the potential rate of spread of an invasive and the probable risks, impacts, and costs point out the need for entirely new approaches to hybrid predictive modeling—models that combine temporal, spatial, stochastic, mechanistic, socioeconomic, and scenario-based approaches. While many of the underlying methods required for these advances are well understood, their specialization to risk analysis for invasive species remains largely uncharted territory (Schnase *et al.*, 2002a).

Finally, aggregating this information in ways that allow decisionmakers to systematically evaluate containment potential, costs, and opportunity costs and make reasoned trades against legal mandates and social considerations will require a new generation of decision support environments tailored to the needs of invasive species risk analysis. Again, many of the basic components of such an infrastructure exist, but as an uncoordinated collection of capabilities. The ultimate challenge for information science and technology will be to assemble capabilities, both old and new, into a framework that is optimized to the unique complexities of invasive species risk analysis (Schnase *et al*., 2000)

6. THE CHALLENGE: TO SELECT PRIORITY SPECIES AND PRIORITY SITES

Often, land managers responsible for invasive species management ask two simple questions: Where is it, and How do I kill it? The underlying challenge is really to select priority species of plants, animals, and diseases for control in a constantly changing triage approach. At present, some widespread species for which there is little hope of containment or control might have to be put on the back burner, while easily contained species get our attention. Local and regional decisions and priorities on species and sites will be set based on a mix and match of the criteria outlined above—hopefully, in cooperation with other local entities since propagules and species cross boundaries like the wind.

Sharing data, modeling tools, expertise of all types, and on-the-ground knowledge is the first step toward effective risk analysis and management. Coordinated efforts will be far superior and cost efficient to uncoordinated efforts. Integrated teams of taxonomists, survey and monitoring specialists, economists, landscape ecologists, modelers, remote sensing specialists, and information technology experts are needed to meet invasive species' challenges at local to international scales. A high degree of public awareness and public involvement (i.e., volunteer networks) may be needed to populate databases to quantify the abundance and distributions of many invasive species.

Finally, predictive modeling and synthesis will become increasingly important in risk analysis for biological hazards. New species are likely entering the country each week. Even if only a small fraction of these species become established, and a fraction of those spread and cause harm (e.g., like zebra mussels have since the 1970s, West Nile virus has since 1999), then the potential high cost of ignoring or not containing invasive species must be considered. Risk analysis for harmful invasive species will require interdisciplinary scientists and modelers to work closely with agencies, nongovernment organizations, and communities to reduce risk and the enormous costs to the American people. An ounce of prevention (and science-based early detection, rapid response, and restoration) will be worth a pound of cure.

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