Review of Methods for Developing Regional Probabilistic Risk Assessments, Part 2: Modeling Invasive Plant, Insect, and Pathogen Species

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Abstract

We reviewed probabilistic regional risk assessment methodologies to identify the methods that are currently in use and are capable of estimating threats to ecosystems from fire and fuels, invasive species, and their interactions with stressors. In a companion chapter, we highlight methods useful for evaluating risks from fire. In this chapter, we highlight methods useful for evaluating risks from invasive species.

The issue of invasive species is large and complex because there are thousands of potential invasive species and constant movement of new and established plants, plant material, pests, and pathogens. Adequate data are not always available to support rigorous quantitative modeling of the different stages of invasion. However, even a semiquantitative rule-based approach can help to identify locations that contain host species susceptible to specific pathogens or insect pests, and where propagules are more likely to enter based on the current locations of the invasive species, ports of entry, and methods of spread. Predicting long-distance movement is much more difficult, as such events are rare, often poorly understood, and are often influenced by human behavior. Even so, published methods to make probabilistic predictions of pest establishment could be expanded to provide quantitative estimates of spread beyond an initial port of entry. Many invasive species are transported along roads, and so road networks provide some information about the likelihood of introduction into a new region.

Models based on fundamental biological and physical processes, such as population demographics and movement of organisms, can be more robust than purely statistical approaches. Process-based models may better support extrapolation beyond the range of available or historical data because they use predictor variables that represent physical and biological processes. However, even simple correlative approaches may be useful to quantify the overlap in spatial distribution of stressors and ecological receptors as a screening-level analysis. Furthermore, if predictors are chosen carefully, they may represent important processes. For example, data on nonindigenous species may be quite useful for predicting the occurrence of much rarer invasive species because the correlation is based on the key processes of human-influenced transport, establishment, reproduction, and dispersal of propagules. Ecological niche-modeling approaches are useful because they can use data from museum collections in other countries to make estimates of potential new range areas in the United States. Other spatial data such as road networks may also be useful to predict the number of nonindigenous species or presence of a particular species. Such relationships may also support extrapolation to future conditions if there will be more roads or a higher traffic volume.

As for any regional stressor, the use of multiple models and a weight-of-evidence approach would help to increase confidence in predictions of ecological risks from invasive species. Two approaches to predicting the risk of Asian longhorned beetle (*Anoplophora glabripennis* Motschulsky) throughout U.S. forests make quite different predictions because they focus on different stages in the process of establishment and spread, thus combining such approaches should result in more robust predictions. Invasive species management should be addressed at multiple spatial scales, including reducing importation of new species at border crossings and ports, national and regional mapping of locations of invasive species, methods to reduce long-distance transport, and methods to reduce local movement.

Keywords: Ecological risk assessment, invasive species, probabilistic risk assessment, regional risk assessment, risk analysis.

Introduction

This review provides an overview of issues in probabilistic risk modeling at the regional scale and suggestions for productive directions for future risk assessments and research. Invasive nonindigenous species are a serious and increasing threat to many ecosystems throughout the United States (NRC 2002, Pimentel 2005). For example, invasive species are implicated as threats for more than half of all endangered species in the United States (Wilcove and others 1998). Invasive species are also altering fire regimes, hydrology, nutrient cycling, and productivity of ecosystems in the Western United States, particularly rangelands and riparian areas (Dukes and Mooney 2004). Plant species such as yellow star-thistle (*Centaurea solstitialis* L.), other Centaurea species, and cheatgrass (*Bromus tectorum* L.) have overtaken large areas of native ecosystems in the Western United States (LeJeune and Seastedt 2001). Leafy spurge (*Euphorbia esula* L.), knapweeds (*Centaurea* sp.), tamarisk (also known as salt cedar, *Tamarix ramosissima* Ledeb.), nonnative thistles, purple loosestrife (*Lythrum salicaria* L.), and cheatgrass are some of the most severe problems on national forest lands. For example, the number of counties in Washington, Oregon, Montana, and Wyoming where yellow star-thistle has been found has been increasing exponentially during the last 100 years (D'Antonio and others 2004). Furthermore, the number of new exotic species has increased roughly linearly over this time period, reaching a total of nearly 800 by 1997 (D'Antonio and others 2004). Annual costs of selected nonindigenous species in the United States have been estimated at $120 million (Pimentel and others 2005). However, this estimate does not account for all effects of invasive species on rangelands and forests (Dukes and Mooney 2004), and it is clear that such costs are substantial. Despite the difficulty in quantifying economic damage, there is substantial evidence suggesting that invasive species have many deleterious effects in ecosystems in the Western United States, and that improved management of invasive species in wildlands is crucial (D'Antonio and others 2004). For example, tamarisk alone has been estimated to cost $133 to $285 million per year (in 1998 U.S. dollars) for lost ecosystem services including irrigation water, municipal water, hydropower, and flood control (Zavaleta 2000).

Various aspects of invasive species biology and ecology, as well as policy and management issues (NRC 2002), are addressed in many published reviews. We will review briefly some key issues, but the focus in this piece is on modeling methods suitable for spatially explicit probabilistic risk assessments for invasive species. This chapter, and a companion chapter addressing fire (Weinstein and Woodbury, this volume), present results of a project sponsored by the U.S. Department of Agriculture (USDA) Forest Service, Western Wildland Environmental Threat Assessment Center during its development; but these results should not be construed to represent the views of the center nor its personnel. The overall goal of our project was to identify promising methods for analyzing ecological risks to forest, rangeland, and wildland ecosystems from multiple stressors. The results of such risk analyses are intended to provide information useful for strategic planning and management of wildlands including national forests. The specific goal of this chapter is to identify modeling approaches suitable for making spatially explicit, probabilistic estimates of ecological risks from invasive plant, insect, and pathogen species throughout large regions such as the Western United States. Such modeling approaches ideally should be capable of:

1. Calculating risk of a detrimental environmental effect.
2. Using spatially heterogeneous environmental data to drive calculation of risk at different points throughout a region. Spatial scales of interest include landscape, sub-State region, State, region of the United States, or the entire conterminous United States.
3. Relying primarily on available regional (in United States, state or multi-State) or national data.
4. Being useful for many species, not just a single invasive species.
5. Modeling effects of interaction among multiple stressors.
6. Modeling effects of changes in environmental conditions in the future.

We review selected modeling approaches relevant to the goals listed above, and more detailed analyses of specific aspects of invasive species assessment and management are provided by other chapters within this broader work.

Stages of Invasion and Risk Assessment Frameworks

This section provides an overview of the stages of the invasion process, key factors that affect these stages, and different frameworks that can be used to assess risks due to invasive species. The process by which a nonindigenous species becomes an invasive species can be divided into the following five stages:

1. Uptake/entry into transport system
2. Survival and transport to the United States via land, air, or water, with or without vectors
3. Initial establishment—survival and reproduction
4. Local dispersion
5. Widespread dispersion

Three classes of key factors influence the likelihood that a potential invader will pass through each stage: (A) propagule pressure, (B) physicochemical requirements of the potential invader, and (C) community interactions (Colautti and MacIsaac 2004). However, even successful modeling of all stages of the invasion process still does not address the likelihood or degree of damage caused by the invasive species. For this purpose, an ecological risk assessment approach is required.

The topic of invasive species has begun to be addressed by practitioners of ecological risk assessment (Andersen and others 2004a, 2004b; Stohlgren and Schnase 2006). Andersen and others (2004a, 2004b) reviewed the regulatory framework for invasive species in the United States and some of the issues in extending the approach to ecological risk assessment (originally developed for contaminants) in order to address biological stressors such as invasive species. They also provide information about a series of articles of the journal "Risk Analysis" that report the results of a joint workshop between the Society for Risk Analysis Ecological Risk Assessment Specialty Group and the Ecological Society of America Theoretical Ecology Section. In addition, they identify research needs for this field. Of relevance to this chapter, they suggest that "Spatially explicit, multiscale decision-support systems will contribute to better decisionmaking through enhanced credibility, an explicit and direct relationship with managing for sustainability, and explicit illustration of trade-offs and the cost of inaction." Presented in one of the articles in this series is a model of establishment risks for Asian long-horned beetle (*Anoplophora glabripennis* Motschulsky) introduction via solid wood packing materials (Bartell and Nair 2004). This approach estimates both the probability of establishment at the port of entry and the probability of spread based on environmental factors, host availability, and traits of the invasive species. Uncertainty in key parameters is investigated by means of Monte Carlo analysis. Additionally, there is investigation of the efficacy of different management techniques. Integration of quantitative risk analysis and quantitative analysis of management options within a single analytical framework is much too rare and should be applied more widely. Another article in this series describes how the conceptual model in the relative risk model can be applied to predict the effects of invasive species (Landis 2003). This approach is promising in that it is capable of addressing multiple stressors simultaneously at the regional scale by means of a ranking procedure. Although complete risk assessments are not reported in this article, it illustrates how invasive species risk can be analyzed at the regional scale in the context of multiple stressors and multiple endpoints. A case study of this approach has been implemented for a European green crab (*Carcinus maenas* L.) for a region of Washington State (Colnar and Landis 2007).

Transport to the United States and Within U.S. Regions

Most exotic plant species have been introduced to the United States intentionally, whereas most insects and pathogens have entered the United States unintentionally (Mack and Erneberg 2002). Global travel and trade have increased the amount of plant material, wood, and wood products moving into U.S. ports, increasing the likelihood of introduction of invasive plants, insects, and pathogens. By 2020, it has been predicted that more than 100 new insect species and 5 new plant pathogens will become established (Levine and D'Antonio 2003). A particularly high-risk pathway for forest insects and pathogens is importation of raw logs (Tkacz 2002). As an example for the Pacific Northwest, surveys of ports, port areas, mills and businesses known to have received or handled imported wood or wood products from 1996 to 1998 found seven species of wood-boring beetles from Asia, Europe, and the Eastern United States (Mudge and others 2001). For the United States as a whole, inspections of all types of products in four cargo pathways at ports and border crossings found the highest rate of insect introductions in refrigerated maritime cargo, with 1 new insect species found in every 54 inspections (Work and others 2005). It was estimated in this study that fewer than half of such new species are detected, and 42 insect species may have become established from 1997 to 2001. These species do not necessarily pose a high risk of widespread infestation or damage, but they do indicate that exotic species are entering the United States at an alarming rate. Many of the issues of invasive species transport and establishment from other countries to the United States also apply to establishment of new populations owing to long-distance transport of invasive species among regions in the United States. Gypsy moth (*Lymantria dispar* L.) is an example species known to cause severe infestation and damage in Eastern U.S. forests (Liebhold and Tobin 2006). Gypsy moth has been long established in the Eastern United States but has been prevented from establishing, to date, in the Pacific Northwest owing to surveillance and eradication efforts (Hayes and Ragenovich 2001).

To manage invasions and reduce risks, it is vastly more cost-effective to prevent establishment, or eradicate an invasive species as soon after entry as possible (Simberloff 2003, Stocker 2004). However, most invasive species are difficult to locate and may not appear to present any significant risk to ecosystems until they have become well established, often many decades after introduction. Thus, most management and control efforts focus on severe known problems rather than preventing future severe problems. Also unfortunately, it is difficult to predict which nonindigenous species will become invasive, and which invasive species will become severe problems (Smith and others 1999). A number of initiatives have been undertaken in the United States to address various aspects of invasive species monitoring, risk assessment, and management owing to the severity of problems caused by invasive species.

Existing National Invasive Management Programs

A number of international, national, and regional efforts are underway to attempt to reduce the risks posed by invasive species. Some of these efforts for the United States are discussed briefly below, with a focus on programs related to forest and rangeland ecosystems. It is beyond the scope of this review to discuss all international programs that may provide valuable information for invasive species in the United States. However, some sources of global information are mentioned in the subsequent section on invasive species databases.

The National Invasive Species Council (NISC) consists of eight Federal departments and was formed in 1999 by Executive Order 13112. The NISC 2001 National Management Plan called for development of a risk analysis system for nonnative species by 2003. The NISC is intended to provide a gateway to information, programs, organizations, and services about invasive species. Their Web site (http://www.invasivespecies.gov) provides information about the impacts of invasive species and the Federal government's response, as well as select species profiles and links to agencies and organizations dealing with invasive species issues.

The USDA Animal and Plant Health Inspection Service (APHIS) protects not only agricultural but also forest, rangeland, and wetland ecosystems. APHIS works closely with the USDA Forest Service and the U.S. Department of the Interior's Bureau of Land Management, National Park Service, and Fish and Wildlife Service. APHIS conducts risk assessments with a dual mission to promote international trade and prevent invasive species that may cause serious harm from entering the United States. Some APHIS activities focus on protecting and managing endangered species as well as migratory bird populations. APHIS maintains the Port Information Database, and there is great potential to strengthen and make broader use of this database for understanding the pathways taken by invasive species entering the United States (NRC 2002).

The USDA Forest Service, working in conjunction with Federal, State, tribal, and private partners, has developed the Early Warning System (EWS) to detect and respond to environmental threats to forest lands in the United States. The EWS comprises many existing programs, along with new initiatives such as the Western Wildland Environmental Threat Assessment Center and the Eastern Forest Environmental Threat Assessment Center. The EWS addresses potential catastrophic threats such as insects, diseases, invasive species, fire, weather-related risks, and other episodic events. The system is intended to:

1. Improve understanding of the crucial elements involved in early detection and response to environmental threats.
2. Help identify and remedy weaknesses in the current system of early detection and response.
3. Aid for strategic planning and resource allocation.

There are many groups both within and outside the Forest Service that participate in the process of detecting and responding to threats to forests. Further information about some component groups that conduct regional risk analyses is presented in other chapters in this volume. Further information about the EWS is available at the following Web site: <http://www.fs.fed.us/foresthealth/programs/early_warning_system.shtml>.

The National Aeronautic and Space Administration (NASA) and the U.S. Geological Service (USGS) are developing a National Invasive Species Forecasting System (ISFS) for the management and control of invasive species on Department of Interior and adjacent lands. The system provides a framework for using USGS's early-detection and monitoring protocols and predictive models to process remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS), the Enhanced Thematic Mapper, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer as well as commercial remote sensing data. The goal is to create on-demand, regional-scale assessments of invasive species patterns and vulnerable habitats. Additional information can be found at the following Web site: http://bp.gsfc.nasa.gov/. This approach has recently been used to predict the relative suitability of all areas in the conterminous United States for tamarisk, an invasive woody shrub (Morisette and others 2006). This analysis is reviewed below under the heading of USGS and NASA Invasive Species MODIS-Regression methodology.

Within the USDA Forest Service, the establishment of the two Threat Assessment Centers is a key part of the strategy for improving the management of invasive species. These efforts build upon ongoing programs and projects such as the Forest Inventory and Analysis Program (including Forest Health Monitoring) and Forest Health Protection. Further information about the strategies of these agencies for invasive species management is provided at the following Web site: http://www.off-road.com/land/invasive_species_strategy.html. Recommendations for control of invasives in rangelands are provided at the following Web site: http://www.fs.fed.us/rangelands/ecology/invasives.shtml

The USDA Forest Service's Forest Health Technology Enterprise Team (FHTET) is using an expert opinion approach to model risks of invasive pests and tree pathogens at the national scale for national strategic planning purposes. Potential tree mortality risk is modeled based on expert opinion, forest inventory data, and other GIS (geographic information system) data (Marsden and others 2005), also see the following URL: http://www.fs.fed.us/foresthealth/technology/products.shtml. Further discussion of this approach is presented below under the heading of "FHTET national risk map."

Availability of Spatial Data

Many kinds of regional data may be useful for developing regional probabilistic risk assessments, including land cover and land use data, transportation networks (e.g., roads and trails), hydrography, climate, digital elevation models, etc. Many such databases are available in GIS format from the National Atlas, which also includes data on selected invasive species (http://www.nationalatlas.gov/atlasftp.html). Data on land use is available from the National Land Cover Characterization database that is being compiled across

States as a cooperative mapping effort of the Multi-Resolution Land Characteristics Consortium. Landcover databases are being developed by bioregion based on remotely sensed imagery acquired from 1999 to 2003 and are complete or nearly complete for most portions of the United States, including the West Coast and much of the Southeast (http://www.mrlc.gov/mrlc2k_nlcd.asp). It is beyond the scope of this review to discuss all of these types of data, or even all types of databases specifically on invasive species, but a brief overview of invasive species survey data is presented below.

At the global scale, the Global Invasive Species Information Network is developing an online registry of data sets related to nonnative species (Simpson 2004), and ongoing efforts are being made to develop linkages among national and multicountry invasive species databases (Simpson and others 2006). The Global Invasive Species Programme (Mooney 1999) provides an online list of invasive species databases, including those covering the conterminous United States, Alaska, and Hawaii (http://www.gisp.org/links/index.asp). In the United States, a survey was undertaken recently to identify data sets of nonnative species at county, State, region, national, and global scales (Crall and others 2006). Based on a literature survey, Internet search, and responses from surveys sent to 1,500 experts, a total of 319 data sets were identified, and metadata were collected for most data sets (79 percent). Of the total, 57 percent are available online (see the following Web site for further information: http://www.niiss.org). Categories of data sets for which metadata are available consist of the following: 77 percent cover vegetation, 38 percent cover vertebrates, 77 percent cover invertebrates, 14 percent cover pathogens, and 9 percent cover fungi. Note that these percentages sum to greater than 100 percent because some data sets cover multiple taxa or categories. The scale of data sets for which metadata are available are as follows: 33 percent are at the county scale, 20 percent at the State scale, 17 percent at the multi-State regional scale, 15 percent are national, and 14 percent are global. Although this number of data sets is encouraging, the authors note that only 55 percent of the data sets have a quality assurance and quality control procedure, suggesting that the accuracy of many data sets may be questionable or undetermined.

Other sources of data useful for regional assessments of invasive species are databases developed by the Forest Inventory and Analysis (FIA) Program of the USDA Forest Service (http://fia.fs.fed.us/). The FIA Program collects data for all land meeting a specific definition of forest land in three phases. Historically, Phase 1 has been based on aerial photography, but now satellite remote sensing imagery is being used. Phase 1 points are used to identify forested and nonforested locations. Phase 2 includes ground measurements such as tree species, height, diameter, disturbance, and stand age on more than 100,000 stratified sampling plots across the country. Historically, the focus was on timber resources that are available for potential harvest, but during recent decades there has been increased emphasis on a broader suite of forest characteristics including forest health and invasive species. In particular, Phase 3 sampling is done on a subset of plots to determine the species, abundance, and spatial arrangement of all trees, shrubs, herbs, grasses, ferns, and fern allies (horsetails and club mosses). This Phase 3 sampling was begun as a separate program called Forest Health Monitoring but is now administered through the FIA Program. As an example, a pilot study collecting Phase three data on plots throughout Oregon found at least 1 nonnative species on 70 percent of all forested plots, and 20 percent of plant cover was nonnative in one of 10 forested plots (http://earthscape.org/r1/ES16479/pnrs_science%20update.pdf; note: membership is required to access this Web site, but free trial membership is available). In addition to data specifically on invasive species, the Phase 2 FIA data are a valuable source of vegetation data because they have been collected in statistically designed surveys for decades. Information on forest type, stand age, and disturbance history are available and can be used in conjunction with data on invasive species to predict vulnerability of forest stands to invasion. Such an approach is underway in the Southern United States (Ridley and others 2006). Phase 2 FIA data are also being used in conjunction with other data to develop regional and national vegetation databases in other research programs including LANDFIRE. See the topic "Conclusions Concerning the Use of Fire Modeling Systems" in Weinstein and Woodbury (this volume).

Review of Selected Methodologies

In this section, we review selected modeling approaches relevant to the goals listed above in the "Introduction" section. The focus is on invasive species of concern for the Western United States, particularly forest and rangeland ecosystems. Examples were selected to cover a range of analytical techniques with an emphasis on the State or regional scale. In addition, we selected examples of two different methods applied to an invasive pathogen that is the causal agent of sudden oak death disease (*Phytophthora ramorum* Werres, de Cock & In't Veld) and two methods applied to an invasive insect: the Asian long-horned beetle.

Climatic and Ecological Niche Models

The most common and readily applied approaches to predicting the risk of invasive species occupying sites across a large region rely on biogeographical distribution models. These models are based on information about the biophysical factors that limit where a species can survive. Such models are known as bioclimatic envelope models, biogeographical distribution models, and (ecological) niche models. Such models are generally correlative and may be either statistically based or rule based. As applied to invasive species, such approaches typically attempt to map which parts of a region are suitable for the invading species, and suitability is typically based on habitat requirements. For pests and pathogens, the simplest approach is to map the presence or absence of suitable hosts. Such maps are typically developed from available regional data sets, which often provide relevant but not necessarily ideal data for a particular invasive species. Such maps may be useful for strategic planning at the regional scale, but may be of limited use for managing specific areas presuming that the managers of those areas already know where different species occur.

Niche models typically identify habitats for invasive species based on records of their presence at known locations. Such records can be obtained from museum collections such as herbaria, but currently, only 5 to 10 percent of such data are available in electronic form worldwide (Graham and others 2004). To define the niche or bioclimatic envelope, biophysical data for each such location are often extracted from regional databases, usually in a GIS. The most important distinction among such approaches is whether they use absence data in addition to presence data. In other words, whether locations where the invasive species does not occur (absence) are used to define biophysical conditions that are outside of the niche. Either approach is problematic for invasive species because, typically, they have not yet occupied all possible sites. Thus, sites where the species doesn't occur may not necessarily provide information about the species niche or requirements; instead, those may be sites that the invasive species haven't yet reached. Presence and absence data can be obtained from the native region of the invasive species, but the species may have a different niche in the part of the world it is invading, as compared with its native region. However, use of data from the native region may be the only reasonable choice for species that have not become widely established in the United States. Even so, there may be substantial uncertainty in such predictions until a species becomes widely established. For example, an analysis of purple loosestrife (a common invasive species in Eastern United States wetland areas) determined that a reliable prediction of the current nonnative distribution in North America was only possible 150 years after initial establishment (Welk 2004).

Many variations of the niche approach are used to predict the niche of the invasive species including:

1. Simple ranges for factors based on mean climatic variables such as the widely used BIOCLIM and DOMAIN models.
2. Fuzzy rather than crisp calculations of the niche (Robertson and others 2004).
3. The use of spatial statistical techniques and newer computational approaches, such as genetic algorithms and support vector machines.

We have evaluated a few examples of such approaches below, with a focus on the Western United States. For each of these examples, we discuss how they meet the criteria listed above.

GARP Niche Modeling Approach

In this family of approaches implemented in a software tool, the potential range of invasive species is predicted based on point data from the species native home range and spatial data including mean annual temperature, rainfall and elevation (Anderson and others 2003, Costa and others 2002, Godown and Peterson 2000, Peterson 2001, Peterson and Cohoon 1999, Peterson and Kluza 2003, Peterson and others 2003b, Stockwell and Peterson 2002, Underwood and others 2004; also see http://www.lifemapper.org/desktopgarp/). This approach shares many features with other approaches to predict ecological niches based on bioclimatic data, including climate envelope modeling and other methods for niche modeling. All of these approaches assume that bioclimatic predictor variables (for example, mean annual temperature and precipitation) control the native distribution of an invasive species, and these factors will also control the potential distribution in the United States This technique differs from others because it uses a machine learning method (also known as artificial intelligence) named Genetic Algorithm for Rule-Set Prediction (GARP). Based on only 15 to 20 records of locations of a species from its native home range (species input data), the method can predict the potential distribution (home range, or niche) of a species. This approach has been used by its developers to model the niche of both invasive species and noninvasive species. The user needs to provide species input data of known points where the species has been found in its native region. These data should be well distributed throughout the species native range and need to be georeferenced. The user also needs to provide environmental data covering the entire area for which predictions are desired, including mean annual temperature and precipitation (modeled surfaces). Potentially, many other input data could be used such as remote sensing images, but they might need to be available for both native region and the analysis region.

The software used is desktopGARP, which can be downloaded from the following Web site: http://nhm.ku.edu/desktopgarp/. The user selects a type of inferential tool, such as logistic regression, or bioclimatic rules. The input data are then divided into training data and validation data. The software generates pseudodata via resampling, and then iteratively tries a large number of rule sets, continuing either until there is no further improvement in the predictions, or 1,000 iterations. The output from the model is a map of species niche as presence/absence, with some confidence values. Modeling may be done for either counties or for grid cells (pixels). The primary prediction is whether a county or a pixel is contained in the species potential (fundamental) niche. A measure of likelihood is generated by using multiple models, and assigning higher likelihoods to counties or pixels predicted to be included in the niche by multiple models (Peterson and others 2004).

In the following citations, only one predicted value is made per county, although the approach could be extended for finer grain analyses if input data are available at finer scales. The methodology (Peterson 2003) and its use to predict the distribution of four alien plant species in North America for a single point in time (the fundamental niche) are described in the references reviewed herein. Invasive plant species analyzed to date include Hydrilla (*Hydrilla* L.C. Rich.), Russian olive (*Elaeagnus angustifolia* L.), sericea lespedeza (Lespedeza cuneata (Dum.-Cours.) G. Don), and garlic mustard (*Alliaria petiolata* (Bieb.) Cavara & Grande) (Peterson and others 2003a). To predict the spread of Asian long-horned beetle, the GARP approach has been combined with a spatial model of spread originally developed for forest fire (Peterson and others 2004).

The GARP approach has several strengths for the regional risk analysis of invasive species, which are as follows:

1. It has been applied to a number of taxa of invasive and noninvasive species in the United States and elsewhere.
2. A freely available software tool has been developed that implements this approach.
3. Data requirements for this approach are modest.

Most weaknesses of the GARP approach are shared by all niche modeling approaches, which include:

1. Not all of the stages of the invasion process are modeled.
2. Only presence or absence of a species is predicted, not effects of invasive species.
3. Results may be biased, depending on the

source of data and the use of pseudo-absence data (Graham and others 2004).

Other approaches such as support vector machines and generalized additive model (GAM) approaches may be less biased and provide more optimal statistical solutions (Elith and others 2006, Stockwell 2005), but see also Anderson and others (2003) for improving on model selection methods.

FHTET National Risk Mapping Approach

This approach is also a family of related approaches to predict tree mortality risk owing to an invasive insect or pathogen based on expert opinion, forest inventory data, and other GIS data (Marsden and others 2005), and also consult FHTET products Web site: http://www.fs.fed.us/foresthealth/technology/products.shtml). Specifically, predictions are made of the potential basal area loss of susceptible tree species owing to an invasive insect or pathogen. The location of suitable host species is interpolated using inverse-distance weighting based on forest inventory data. A multi-criteria risk ranking model is developed based on expert opinion about the factors that influence pest or pathogen establishment, spread, and tree mortality. An iterative process is used to develop risk maps, so the experts and analysts can alter the weighting of difference factors to adjust the maps to match expert opinion. This approach has been used to predict the potential effect of oak wilt in the North Central States and of wood wasp (*Sirex noctilio* Fabricius) throughout the conterminous United States: (http://www.fs.fed.us/foresthealth/technology/invasives_sirexnoctilio_riskmaps.shtml).

The following are the key required input data and their sources:

1. Principal U.S. ports - Army Corps of Engineers, Waterborne Commerce, Foreign Cargo Statistics.
2. Markets for wood products - Federal High-way Administration, Freight Management and Operations, Freight Analysis Framework, Highway Truck Volume and Environmental Systems Research Institute's (ESRI) polygon data.
3. Distribution centers - National Transportation Atlas Database.
4. Species occurrence and basal area of individual tree species – USDA Forest Service, Forest Inventory and Analysis (FIA), National and New York State Christmas Tree Association Web sites.
5. Road density and distance to road – U.S. Geological Survey, Heterogeneous Distribution Indicator.

Use of this approach requires one or more experts on the pest or pathogen, expertise in the use of FIA data, and expertise in GIS software. The spatial scope is the conterminous Unites States for a single time period. Required software includes ArcView 3.x, Spatial Analyst ModelBuilder (ESRI, Inc.), and IDRISI 32 (a raster GIS software package). Model output includes maps of predicted occurrence based on (1) hosts known to be susceptible and (2) hosts suspected to be susceptible.

For regional and national risk analysis, the approach of mapping factors that influence a stressor and then combining these factors with weightings derived from expert opinion are intuitively appealing and fairly common. This flexible, iterative expert opinion-based approach can be used for virtually any pest or pathogen, and a risk map can be generated fairly quickly because the system is already in place. Other strengths of this approach include the use of national FIA data and the quantification of potential damage in terms of tree mortality. However, the flexible expert opinion-based approach is also a weakness because it is so open-ended, subjective, and difficult to validate. To date, it does not appear that an attempt has been made to determine which environmental factors were actually associated with pest presence, or to quantify uncertainties in GIS layers or predictions. In contrast, a statistical inference approach that made quantitative predictions of pest occurrence would be more useful because it could be better tested against validation data.

Meentemeyer Sudden Oak Death Approach

Meentemeyer and others (2004) used a rule-based function to predict spread of sudden oak death pathogen distribtions in grid cells (30 by 30 m) throughout California. A prediction was made of the likelihood of presence of the disease based on rules derived from expert opinion and published data on plant species susceptibility, pathogen reproduction, and host climate. This method is focused on evaluating a single risk, the probability of oaks on a given site being infected by *P. ramorum*. More specifically, the method begins with mapping five predictor variables in a GIS and then using a set of rules to determine the risk of infection based on these predictor variables. The predictor variables are host species index, precipitation, maximum temperature, minimum temperature, and relative humidity. Host species index is weighted three times as strongly as precipitation and maximum temperature, which in turn are weighted twice as strongly as relative humidity and minimum temperature. Each variable is classified on a relative index, with host scored on a scale from 0 to 10, precipitation, maximum temperature, and humidity scored from 0 to 5, and minimum temperature scored from 0 to 1. The model was tested against 323 field observations in California. The model generally predicted higher risk for sites where *P. ramorum* is currently present and lower risk for sites where it is currently absent. However, it appears that approximately 20 percent of low-risk sites were infected.

Input data for the model include host susceptibility, pathogen reproduction, and host climate suitability. Like many modeling approaches, this approach requires expertise in GIS and database analysis. The model output is in the form of a map with estimated risk of occurrence of the pathogen at a single time period – movement of the pathogen is not modeled. The spatial scope includes all of California, and the map unit is landscape cell (30 by 30 m). The approach uses the CALVEG database (USDA Forest Service RSL 2003) for vegetation alliance and presence of *P. ramorum* and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for elevation-based regression extrapolations from base weather stations for climate data, which are available for the conterminous United States (http://www.wcc.nrcs.usda.gov/climate/prism.html).

The method meets the criterion of calculating the risk of detrimental environmental effect by mapping the probability of pathogen occurrence in each forest grid-cell and could be extended to predict the presence of pathogens in smaller regions or pixels. But the focus is assessment of effects over a region, specifically bioregions, rather than at all points within a region. The method meets the criterion of using spatially heterogeneous environmental data to drive calculation of risk at different points throughout the Western United States. Potentially, it could be used to evaluate the risk from a number of stressors, but relationships between habitat conditions and probability of stressor occurrence would have to be developed. Potentially, the method could be extended to consider effects of interaction among multiple stressors, but interaction terms would need to be identified and parameterized in a regression model. The approach does not currently consider the effect of changes in environmental conditions over time.

Unfortunately, no attempt was made to determine which environmental factors were actually associated with disease presence. A statistical inference approach that made quantitative predictions of pathogen occurrence would be more useful because it could be better tested against validation data when they become available. The finding that 21 percent of sites predicted to be low risk, yet were found to be infected, suggests that the model has limited predictive power. This limited power is likely due to data limitations as well as lack of precision in rules and weights applied to them. The investigators do state that they plan to use FIA data to improve the predictions. This study was evaluated because it addressed an important risk factor in Western and potentially Eastern U.S. forests, but use of a method that makes more quantitative predictions would be useful in the future.

Nowak Host Range Approach

This approach predicts potential home range of an (invasive) insect or pathogen of trees by modeling the location of suitable host species based on forest inventory data (Nowak and others 2001, http://www.fs.fed.us/ne/syracuse/Data/Nation/InsectPoten.htm). A model of urban forests (UFORE) is used to predict urban forest composition based on data from a limited number of cities in the United States. Predictions are also made of the amount of tree cover that could be lost owing to tree death and the costs of replacing killed trees.

A simple model of spread (moving outward at a constant rate from one location) was used to predict the length of time required for invasion to occur in each major city. This approach has been used to predict the potential effect of Asian long-horned beetle throughout all urban areas in the United States (Nowak and others 2001), and preliminary predictions have been made for nonurban areas (http://www.fs.fed.us/ne/syracuse/Data/Nation/InsectPoten.htm). Preliminary predictions have also been made for the emerald ash borer (*Agrilus planipennis* Fairmaire) (http://www.fs.fed.us/ne/syracuse/Data/Nation/InsectPoten.htm). The main type of required input is appropriate forest inventory data. Model output is in the form of maps of predicted occurrence based on (1) hosts known to be susceptible and (2) hosts suspected to be susceptible. The model has been used at the scale of the conterminous United States for a single point in time.

One strength of this approach is the use of FIA data in conjunction with a model that has been used for many years. Another strength of this approach is the quantification of damage in terms of economic losses of urban trees. For urban trees, such economic losses are quite high, though for wildlands they will be much lower for an individual tree and much harder to estimate for a forested region. A limitation for regional risk assessment and management is that the focus of the model is urban areas. Another limitation, typical of most niche modeling efforts, is that not all steps in the process of invasive dispersion and reproduction are modeled, and that predictions are primarily of the potential host range of the pathogen, not of effects of the pathogen other than economic losses owing to the death of urban trees.

USGS and NASA Invasive Species MODIS-Regression

In this approach, a logistic regression is developed to predict the suitability of each 1-km pixel as habitat for tamarisk throughout the conterminous United States (Morisette and others 2006). Various ground surveys of tamarisk occurrence were integrated into a single database as presence or absence of tamarisk. Land cover, normalized difference vegetation index (NDVI), and enhanced vegetation index (EVI) were derived from MODIS data products. A discrete Fourier transform was used to model a constant amplitude yearly sine wave to each pixel, and the mean, amplitude, and phase of both NDVI and EVI were used as potential predictor variables along with a fitted parameter for each land cover class in a logistic regression model to predict the likelihood of habitat suitable for tamarisk. The ground data were split into a training set to fit the model (67 percent of data) and a validation set (33 percent of data). The best model included land cover, and seasonal variability in NDVI and EVI. The proportion of correctly predicted observations using a threshold of 0.5 was 0.90. The main model inputs are MODIS data and surveys of tamarisk presence. Because it is a regression procedure, many other input data could be used, such as human population density, trail networks, air temperature, etc. The main model output is a relative ranking of the likelihood of suitable habitat for an invasive species.

This general approach would be useful for regional assessments because it uses remotely sensed data that cover the entire conterminous United States. However, for each invasive species, a large database of ground survey data is required. If FIA or other systematic survey data could be used for this purpose, that would make the approach useful for many more invasive species. A limitation of this approach is that it uses statistical correlation to make predictions, thus it cannot readily predict the effect of future environmental conditions such as changes owing to development, changes in hydrology, or changes in regional or global climate. Other examples of logistic regression to analyze invasive species include multiple species in South Africa (Higgins 1999) and Russian knapweed (*Acroptilon repens* (L.) DC.) in Colorado (Goslee and others 2003).

Dark Invasive Species Spatial Autoregressive Approach

This approach uses spatial statistical analysis to predict the distribution of invasive and noninvasive alien plants throughout all bioregions in California (Dark 2004). Spatial autoregressive (SAR) models were used to assess the relationship between alien plant species distribution and native plant species richness, road density, population density, elevation, area of sample unit, and precipitation. Three predictors were found to be statistically significant for both invasive and noninvasive plants: elevation, road density, and native plant species richness. The best model (with all predictors) explained about 80 percent of the variance in the number of alien species in each bioregion. Additionally, there was significant spatial correlation for both invasive and noninvasive alien plants. Both invasive and noninvasive alien plants are found in regions with low elevation, high road density, and high native-plant species richness. Spatial data input requirements include a digital elevation model, precipitation (a modeled surface), road networks, native species richness, and occurrence of alien species. Because it is a regression procedure, many other input data could be used, such as population density, trail networks, air temperature, traffic volume, etc. The model has been applied to all of California for a single time, with bioregions as the map unit. Model outputs include maps of the number of invasive and noninvasive alien species by bioregion. The method could be extended to predict the presence of invasive species in smaller regions or pixels.

This general approach would be useful for regional probabilistic risk assessments because it uses widely available data in conjunction with a flexible spatial statistical approach. Additionally, it predicts the total number of nonindigenous (alien) species within a region. This technique could be feasibly extended to predict the probability of occurrence of invasive species based on the occurrence of noninvasive alien species. This would be very useful because noninvasive species were found to be roughly tenfold more common than invasive species for the bioregions. This would be a useful first step for regional risk assessment for large regions such as the Western United States in order to identify areas with higher overall risk for invasive species. The approach could be improved by using more detailed data on vegetation types rather than bioregions. A limitation of this approach is that it uses statistical correlation to make predictions, thus it cannot readily predict the effect of future environmental conditions, such as changes owing to development, changes in hydrology, or changes in regional or global climate. However, it might be feasible to develop statistically based extrapolations from existing data. For example, if the number of nonindigenous species in a region can be predicted based on some measure of the transportation network, or other environmental factor, one could extrapolate to future conditions with more roads or a higher traffic volume. A future scenario of new road development or greater traffic or both on existing transportation networks could be developed based on planned State and Federal transportation projects. This scenario could be used to predict the subsequent increase in occurrence of nonindigenous species and invasive species.

Guo Support Vector Machine Approach

This method uses a type of machine learning algorithm called support vector machine (SVM) in a niche modeling approach to predict risk of occurrence of sudden oak death throughout California (Guo and others 2005). A useful comparison is made of presence-only (one class SVM) versus presence with pseudo-absence data (2-class SVM). Based on their results, the use of pseudo-absence data does not appear to be a good choice for modeling invasive species—they inherently lead to bias because they conflate environmentally determined absence with absence on account of infestation not having occurred yet in a particular location. Input data include 14 environmental variables including mean annual temperature, mean annual precipitation, distance to roads, distance to patches of hosts, and presence of susceptible species. The use of this approach currently requires an analyst with not only GIS skills, but also substantial programming skill. Also, assistance may be needed from algorithm developers to modify code. Model output is a map of the potential location of the invasive species. The spatial scope includes all of California, and the map unit is a 1-km grid cell for a single time. Two regional databases are used as input data: California GAP and climate surfaces from the DAYMET model (http://www.daymet.org/). The software used is LIBSVM, which is a library of generic support vector machine functions developed by Chang and Lin 2001, as cited by Guo and others 2005. In this approach, risk is calculated only as potential presence of the disease. There are some probabilistic components, but many sources of uncertainty are not quantified.

This approach would be useful for regional probabilistic risk assessments because it is a generic machine learning technique applied to niche modeling. Thus, it could be used for invasive plants, insects, diseases, and possibly other stressors. One-class SVMs appear particularly attractive because they are statistically based and unbiased and theoretically optimum, unlike some other machine learning methods and don't require a lot of model tuning. A weakness of the approach, at least for many potential users, is dependence on a library of computer code functions rather than a more mature and user-friendly software package, and assistance may be required from the library developers to apply the functions in an analysis. This approach also does not account for time, nor does it incorporate spatial processes such as dispersion. It may be difficult to specify weights for each variable. Like all niche models, it is dependent on data quality, and there will likely be issues of spatial support and spatial scaling.

Discussion

The issue of invasive species is large and complex because there are thousands of potential invasive species and constant movement of plants, plant material, pests and pathogens, in addition to established invasive species. It seems clear that the most cost-effective approach is to control invasive species very early in the process of transport from the native range and entry to the United States. This issue has received national recognition as an important threat and should be addressed at the national scale (NRC 2002). Increased international trade is exacerbating the problem, and despite this increase, the budget for APHIS, the first line of defense, has been decreasing in recent decades as a function of the volume of imported material (D'Antonio and others 2004).

Despite the lack of complete data sets and complete information about the biology and ecology of invasive species, it is feasible to develop risk analyses of invasive species at the regional scale that should provide information useful for land managers. Even a semiquantitative rule-based approach can help to identify locations that contain susceptible host species for specific pathogens or insect pests and where propagules are more likely to enter, based on the current locations of the invasive species and methods of spread (for example, Meentemeyer and others 2004, Nowak and others 2001). As discussed above, the use of regional forest inventory data and detailed vegetation mapping based on these and other data provide an important starting point for regional risk assessments of invasive species.

A broad range of niche modeling approaches are useful because they can use data from museum collections in other countries to make estimates of potential new range areas in the United States. Such data provide information about the fundamental niche of the organism, although this information must be evaluated critically by scientists skilled in taxonomy and biogeography and applied with care (Graham and others 2004). The GARP approach would be useful for regional assessments because a software package is available specifically to apply this method to niche modeling. However, other approaches such as support vector machines and GAM approaches may be less biased and provide more optimal solutions (Elith 2006, Stockwell 2005).

As compared to predicting the fundamental ecological niche of a species, predicting the rate of long distance movement is much more difficult because such events are rare, may not be well understood, and may be affected by human behavior. The approach demonstrated recently by Bartell and Nair (2004) to examine pest establishment and spread could be expanded and adapted to provide quantitative estimates of spread beyond an initial port of entry. There is a large body of work in the spatial ecology literature addressing various aspects of the spread of populations and, more generally, the role of space in structuring populations and metapopulations (Tilman and Kareiva 1997). In recent years, there has been an increase in the number of publications using empirical data in conjunction with modeling approaches to predict the spread of invasive plant species. This process is complex because of the rare, but crucial events of long-distance transport, including movement from the native range to the United States. Whereas simple diffusion models may be useful in some instances, the issue of long distance transport by human vectors needs to be addressed (Hastings and others 2005). Some of the methods discussed above included estimates of spread. One such analysis to assess the risk posed by Asian long-horned beetle combined the GARP niche modeling approach with a simple model of spread from likely ports of entry (Peterson and others 2004). This approach makes predictions quite different from those based on analysis of species host range, as discussed above (see "Nowak Host Range").

Models based on fundamental biological and physical processes, such as population demographics and movement of organisms, generally are preferable to correlative statistical approaches. This does not mean that correlative approaches are not valuable for probabilistic regional risk assessments. They may be useful first steps for regional analysis (for example, to quantify the overlap in spatial distribution of stressors and ecological receptors throughout the Western United States). Correlative models such as that of Dark (2004) may be extended with some confidence beyond the range of available data because they use predictor variables that represent physical and biological processes. For example, the distribution of nonindigenous and invasive species was found to be similar, because both must pass through the same environmental filters or stages. The approach of using data on locations of all nonindigenous species to predict the occurrence of much rarer problem-invasive species may be quite useful because the correlation is based on the key processes of human-influenced transport, establishment, reproduction, and dispersal of propagules. In such cases, statistically based extrapolations from existing data should be quite credible and useful. In addition to extrapolating from all nonindigenous species to only invasive species, future environmental scenarios might be developed to predict future risks. For example, one could extrapolate to future conditions with more roads or a higher traffic volume, if the number of nonindigenous species in a region can be predicted based on some measure of the transportation network (Larson 2003, McKinney 2002) or other environmental factor. A future scenario of new road development or greater traffic or both on existing transportation networks could be developed based on planned State and Federal transportation projects. This scenario could be used to predict the subsequent increase in occurrence of nonindigenous species and invasive species.

Risk assessment for invasive species will be most useful if it helps provide information about the degree of potential harm, or damage. For certain invasive plant species, especially serious and common weeds of crop and rangelands, damage can be quantified in economic terms. However, it can be difficult to quantify the ecological effects of many invasive species, especially for effects on wildlands. For example, it has been assumed that purple loosestrife is a serious threat to wetlands in the Northeastern United States, and considerable effort has been made to eradicate it. However, an analysis of ecological effects found little evidence for damage to wetlands (Hager and McCoy 1998), although one recent publication did find some evidence that it can reduce native plant diversity (Schooler and others 2006). The lack of evidence of severe ecological effects in wildland ecosystems does not mean that such effects don't exist. Rather, such a lack of evidence may indicate a lack of research on wildland ecosystem effects and the difficulty in quantifying such effects in wildland ecosystems as compared to highly managed ecosystems such as agricultural row crops. This difficulty in assessing economic damage of invasive species has been recognized as a key challenge for research (Andersen and others 2004a). Despite the challenge, such efforts may be useful, as they may provide evidence that even large expenditures required for removal of invasive species may provide a valuable economic return. For example, it has been estimated that the costs of eradication of tamarisk throughout the Western United States would be fully recouped within 17 years with continued ongoing benefits beyond that time (Zavaleta 2000).

As for any regional stressor, the use of multiple models and a weight of evidence approach would help to increase confidence in predictions of ecological risks from invasive species. As discussed above, two approaches to predicting the risk of Asian long-horned beetle throughout U.S. forests make quite different predictions because they focus on different stages in the process of establishment and spread. All models have some level of uncertainty both in the data used to drive the model and in the calculations made within the model. A focus on uncertainty as an important type of information is crucial for meaningful assessments of invasive species risk. There is strong evidence of the potential for invasion and damage to occur for certain species such as those already on lists of noxious weeds. The strongest predictor for a species is if that species is already an invasive species causing substantial damage in another part of the world. For these species, there is generally quite a bit of information about aspects of their life history that are important for predicting risk, such as host range, reproductive potential, and phenotypic plasticity. However, for other species there is little or no information. For example, the causal agent of sudden oak death in California was only discovered because of unusual mortality and morbidity in California live oaks. Investigation revealed a new species; thus, there was virtually no information about the ecology of the species such as host range, climatic requirements, and reproductive potential. Until such information began to be gathered, it was not possible to make any meaningful prediction of invasiveness or ecological risk.

Finally, risk assessments will not be useful unless they provide guidance for management. Land managers could benefit in particular from regional risk assessments that provide information about potential future risks. Invasive species management should be addressed at multiple spatial scales such as:

1. Reducing importation of new species at border crossings and ports.
2. Conducting national and regional mapping of locations of invasive species.
3. Developing procedures to reduce long-distance transport if possible.
4. Developing local procedures to reduce movement of invasive species.

Because many invasive species become established along roadways and trails, it may be easier to locate and eradicate them before they spread. However, costs of eradication can be very high, and the most cost-effective approaches will be at the national and regional scale, rather than the scale of a single national forest. Quantitative approaches to estimate the costs and benefits of management options are needed. The feasibility of estimating such costs has been demonstrated (Bartell and Nair 2004, Zavaleta 2000), but much more work is required. Developing such estimates by bringing together risk assessors and land managers should be considered in developing regional risk assessments that will help focus on key issues for management.

In summary, we offer the following suggestions to be considered when selecting modeling approaches for probabilistic risk assessment for invasive species at the regional scale:

1. Define management options and formulate the risk problem definition at the same time so that predictions will be useful for making management decisions.
2. Ecosystems are spatially explicit, so use spatially explicit data, such as vegetation type, topography, stream networks, and elevation.
3. Use both socioeconomic and ecological information.
4. Do not assume that the initial conditions of a landscape can all be captured by a few regionalized variables because of the large role that site history often plays in shaping future dynamics.
5. Whenever possible, make quantitative predictions of risks rather than using ranks (such as low, medium, and high). Ranked values can lead to erroneous interpretations because it may not be clear what is meant by a high risk and also because of uncertainty about what happens at the boundaries of the rank categories.
6. Quantify important spatial and nonspatial sources of data uncertainty and address these uncertainties in the analysis.
7. Quantify important sources of uncertainty in model equations, including aggregation and scaling issues, and address these uncertainties in the analysis.
8. Whenever feasible, use multiple models based on different approaches and data.

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