Integrated Monitoring and Information Systems for Managing Aquatic Invasive Species in a Changing Climate

HENRY LEE II,* DEBORAH A. REUSSER,† JULIAN D. OLDEN,‡ SCOTT S. SMITH,† JIM GRAHAM,§ VIRGINIA BURKETT,** JEFFREY S. DUKES,†† ROBERT J. PIORKOWSKI,‡‡ AND JOHN MCPHEDRAN§§

*Western Ecology Division, National Health and Environmental Effects Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2111 SE Marine Science Drive, Newport, OR 97365, U.S.A., email lee.henry@epa.gov

†U.S. Geological Survey, Western Fisheries Research Center, 6505 NE 65th Street, Seattle, WA 98115, U.S.A.

‡School of Aquatic and Fishery Sciences, University of Washington, University of Washington, Box 355020, Seattle, WA 98195, U.S.A.

§Natural Resource Ecology Laboratory, Colorado State University, Campus Delivery 1499, Fort Collins, CO 80523-1499, U.S.A.

**U.S. Geological Survey, 540 North Courthouse Street, Many, LA 71449, U.S.A.

††Department of Biology, University of Massachusetts Boston, 100 Morrissey Boulevard, Boston, MA 02125, U.S.A.

‡‡Alaska Department of Fish and Game, Box 25526, Juneau, AK 99802, U.S.A.

§§Maine Department of Environmental Protection, 17 State House Station, Augusta, ME 04333-0017, U.S.A.

Abstract: *Changes in temperature, precipitation, and other climatic drivers and sea-level rise will affect populations of existing native and non-native aquatic species and the vulnerability of aquatic environments to new invasions. Monitoring surveys provide the foundation for assessing the combined effects of climate change and invasions by providing baseline biotic and environmental conditions, although the utility of a survey depends on whether the results are quantitative or qualitative, and other design considerations. The results from a variety of monitoring programs in the United States are available in integrated biological information systems, although many include only non-native species, not native species. Besides including natives, we suggest these systems could be improved through the development of standardized methods that capture habitat and physiological requirements and link regional and national biological databases into distributed Web portals that allow drawing information from multiple sources. Combining the outputs from these biological information systems with environmental data would allow the development of ecological-niche models that predict the potential distribution or abundance of native and non-native species on the basis of current environmental conditions. Environmental projections from climate models can be used in these niche models to project changes in species distributions or abundances under altered climatic conditions and to identify potential high-risk invaders. There are, however, a number of challenges, such as uncertainties associated with projections from climate and niche models and difficulty in integrating data with different temporal and spatial granularity. Even with these uncertainties, integration of biological and environmental information systems, niche models, and climate projections would improve management of aquatic ecosystems under the dual threats of biotic invasions and climate change.*

Keywords: aquatic invasive species, aquatic invasive species monitoring, climate change, information systems, niche models

Sistemas Integrados de Monitoreo e Información para el Manejo de Especies Acuáticas Invasoras en un Clima Cambiante

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Resumen: *Los cambios en la temperatura, la precipitación y otros factores climáticos y el ascenso del nivel del mar afectarán a las poblaciones de especies acuáticas nativas y no nativas y a la vulnerabilidad de los ambientes acuáticos a nuevas invasiones. Los programas de monitoreo son fundamentales para evaluar los efectos combinados del cambio climático y las invasiones al proporcionar una base de condiciones bióticas y ambientales, aunque la utilidad de un programa depende de sí los resultados son cuantitativos o cualitativos y otras consideraciones de diseño. Los resultados de una variedad de programas de monitoreo en los Estados Unidos están disponibles en sistemas integrados de información biológica, aunque algunos solo incluyen especies no nativas. Además de incluir a las nativas, sugerimos que estos sistemas podrían mejorar mediante el desarrollo de métodos estandarizados que capturen requerimientos de hábitat y fisiológicos y enlacen bases de datos biológicos nacionales y regionales en portales web que permitan la obtención de información de múltiples fuentes. La combinación de resultados de estos sistemas de información biológica con los datos ambientales permitiría el desarrollo de modelos de nicho ecológico que pronostiquen la distribución o abundancia potencial de especies nativas y no nativas con base en las condiciones ambientales actuales. Las proyecciones ambientales de los modelos climáticos pueden ser utilizadas en estos modelos de nicho para proyectar los cambios en la distribución o abundancia de especies bajo condiciones climáticas alteradas y para identificar potencialmente especies invasoras de alto riesgo. Sin embargo, hay un número de retos, como las incertidumbres asociadas con las proyecciones de modelos climáticos y de nicho y la dificultad de integrar datos con diferente granulosidad temporal y espacial. Aun con estas incertidumbres, la integración de sistemas de información biológica y ambiental, los modelos de nicho y las proyecciones climáticas podrían mejorar el manejo de ecosistemas acuáticos doblemente amenazados por las invasiones bióticas y el cambio climático.*

Palabras Clave: cambio climático, especies acuáticas invasoras, modelos de nicho, monitoreo de especies acuáticas invasoras, sistemas de información

Introduction

As the Earth's climate changes, aquatic species will respond to changes in temperature, precipitation, surface flow, sea-level rise, and land-use practices. Changes in species distributions consistent with regional warming during the past century have been reported for several aquatic species, with a general tendency for poleward or elevational range shifts (Sagarin et al. 1999; Root et al. 2003; IPCC 2007). A concurrent "ecological revolution" is the introduction and expansion of invasive species in nearly every aquatic habitat (Lodge et al. 2006). These 2 environmental drivers are intertwined because climate change is likely to alter the distribution and abundance of existing aquatic invasive species (AIS) and the rate of introduction of new invaders (Carlton 2000; Kolar & Lodge 2000; Rahel & Olden 2008 [this issue]).

Managing aquatic ecosystems in the face of both climate change and bioinvasions will be difficult because both processes are subject to many uncertainties. Climate change may not be unidirectional over short time periods or over decadal cycles (e.g., El Niño-Southern Oscillation), and there may be nonlinear or lag effects between climate variability and the resulting short-term and long-term effects on habitat suitability (Burkett et al. 2005; IPCC 2007). Moreover, invaders often exhibit unexplained time lags or population crashes and can hybridize, adapt, and spread while remaining undetected for years (Crooks & Soulé 1999; Simberloff & Gibbons 2004; Stohlgren & Schnase 2006). Native species "invading" new geographical regions as a result of climate change may exhibit some of these same population patterns, further adding to the complexity.

Addressing these complexities for more than a handful of intensively studied species will require the ability to "data mine" the extensive existing information on distribution and abundance of species available from aquatic survey programs. Results from such syntheses can be used to assess the current extent of invasion or to establish baseline distributions with which to evaluate the effects of climate change. Nevertheless, predicting future AIS distributions or population changes in response to climate change requires a modeling approach. One practical approach is to use ecological niche models (also known as habitat models or species-distribution models) that predict distribution or abundance of a species solely on the basis of environmental conditions (Rodriguez et al. 2007). Projecting such future population changes will require data mining of existing environmental conditions to generate the niche models and input of projected environmental conditions from climate models. Given the plethora of data types and sources, one of our objectives here was to introduce researchers in different fields to information sources for aquatic non-native species and climate change. Another of our objectives was to suggest how the existing information systems could be improved and to provide a general framework (Fig. 1) on how these components could be linked to provide the information needed to manage native and non-native species under a range of climate scenarios.

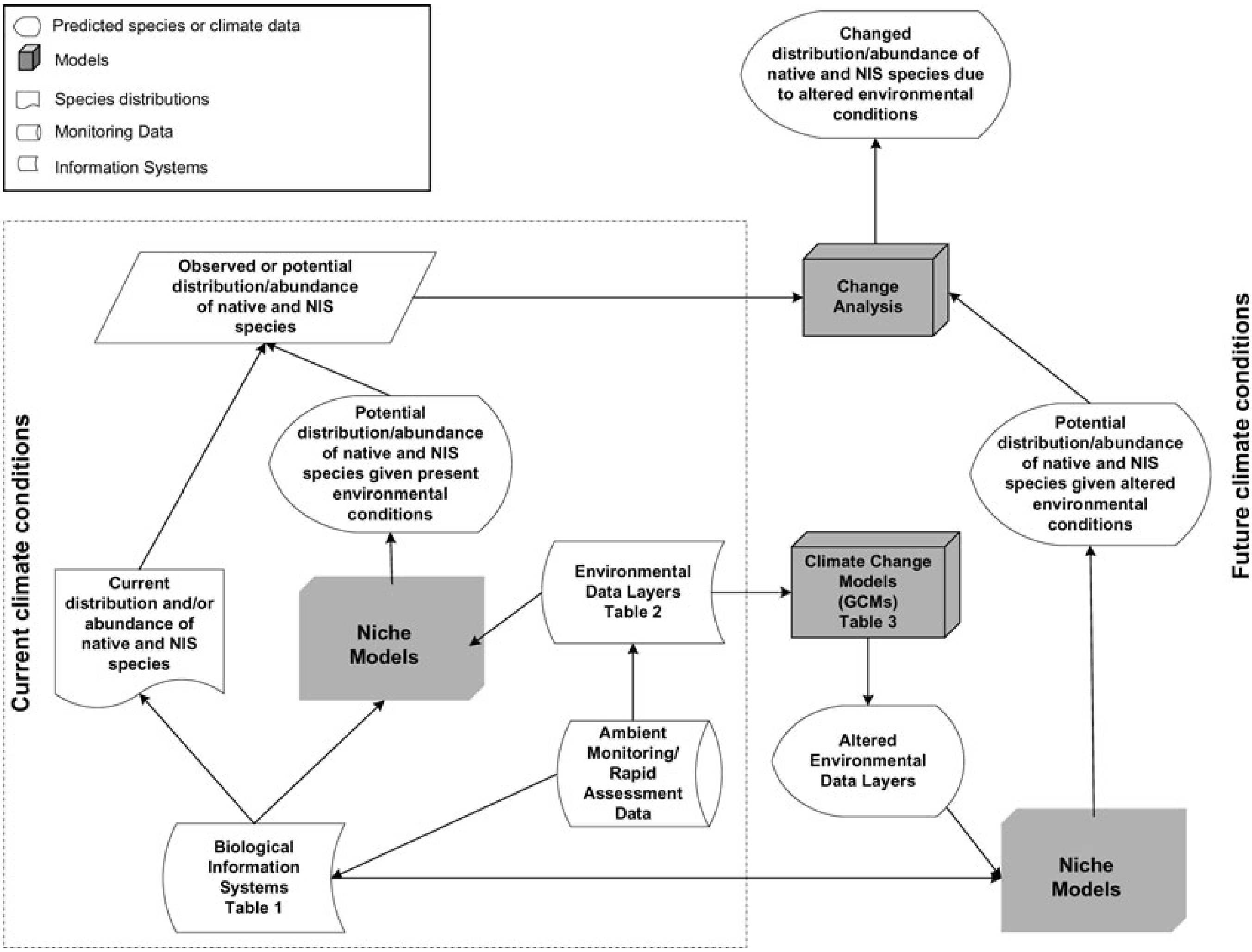

Figure 1. Interrelationships of biotic, environmental, and climate data sources and models in assessing current species distributions and predicting potential changes under climate-change scenarios (NIS, nonindigenous species; GCM, general circulation model).

Monitoring for Native and Non-Native Species

Monitoring surveys provide the foundation for assessments of current ecological condition and provide baseline biotic data to develop niche models. Nevertheless, the sampling design of a monitoring program affects what types of questions can be addressed. In addition to geographical scope and target species or habitat, key design criteria affecting how data can be used include (1) whether a random versus a fixed or nonrandom sampling design was used, (2) whether only non-native or both non-native and native species were sampled, (3) whether abundance and presence data were collected, (4) the sample density (number of samples per area or time period), and (5) whether sites were resampled over time. Another issue important for programs monitoring invasive species is taxonomic resolution and accuracy. Detection of new invaders hinges on the ability to recognize species not included in standard, regional taxonomic references, which requires high-quality taxonomy.

Within the United States, the 2 largest ecological surveys on a national scale are the ambient monitoring programs of the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (EPA). The USGS program is the National Water-Quality Assessment Program (NAWQA; http://water.usgs.gov/nawqa/), which evaluates the ecological condition of streams in a set of watersheds across the United States. The major EPA program is the Environmental Monitoring and Assessment Program (EMAP; U.S. EPA 2002, http://www.epa.gov/emap/index.html), which evaluates ecological condition of surface, coastal, and estuarine waters. Both programs collect abundance data on native and non-native aquatic species, although the primary objective is not to quantify the abundance or diversity of non-natives within a specific area. Differences in these 2 programs illustrate how sampling design can affect the types of questions best addressed by a particular program. The NAWQA uses fixed stations in a limited number of watersheds and is more suitable for detecting short-term temporal patterns and long-term trends at a few representative sites. In contrast, the EMAP program uses a probabilistic sample design to generate areal estimates of ecological condition or population abundance over defined target areas (e.g., biogeographic region) with a known confidence level. Besides meeting the assumption of random samples required for some models, an advantage of a probabilistic design for niche models is that samples are taken over a broader range of habitat types than with fixed stations, thus capturing a greater portion of a species' niche space. Nevertheless, both NAWQA and EMAP are limited to the United States and thus likely truncate the northern and/or southern range of many species.

In contrast to the broad taxonomic surveys conducted by EMAP and NAWQA, invasive-species monitoring focuses solely on non-native species. Invasive-species surveys identify what non-native species presently occur within a region. Several sampling designs for invasive species are possible (Campbell et al. 2007). One approach is to conduct quantitative surveys focused on areas of likely invasion, such as port surveys in Australia (Hewitt & Martin 2001). Advantages of quantitative surveys are that they are repeatable over time and allow rigorous statistical comparisons among sites or over time.

A qualitative approach is the rapid-assessment survey in which a team of taxonomists descends on a specific area and specifically focuses on cataloging as many non-native species as possible within a few days to a week (e.g., Cohen et al. 2005). Rapid assessment surveys of invasive species appear to have been limited to coastal waters, but are also applicable to surface waters and wetlands. An advantage of such surveys is that results are obtained rapidly, with species identified on site to the extent practical. Nevertheless, different surveys are not easily compared because the results depend on the participating taxonomists and sampling is biased toward readily accessible habitats. The greatest strength of rapid-assessment surveys is that they are a cost-effective way to detect new or expanding invaders in high-risk areas and can be used to establish an initial baseline of the presence of non-native species in poorly studied areas.

Field surveys can also be designed to address specific questions related to climate change and invasion dynamics. Although there will be exceptions due to regional-scale environmental patterns (e.g., Helmuth et al. 2002), climate change will often lead to shifts in species' ranges across latitude and elevation. Thus, sampling the expansion or contraction of these leading edge populations may be a sensitive indicator of climate effects (Hellmann et al. 2008 [this issue]), although the low abundance typical at the edge of a species' range can make detecting statistically significant differences difficult.

Biological Information Systems

With the advancements in database and Internet capabilities, results from monitoring programs are increasingly synthesized into biological information systems at regional, national, and international scales (Ricciardi et al. 2000; Simpson et al. 2006). We summarize a number of such systems for aquatic species covering most of the United States in Table 1. The primary utility of these systems is as a source for species distributions or abundances to address questions such as biogeographical patterns of invasion, extent of invasion in specific locations, or the development of ecological niche models. In many cases, no one information source will provide the data needed to generate a comprehensive distribution for a species or the composition of native and non-native species within a location. Rather than attempting to combine all these sources into a single, centralized data source, a more practical approach is a Web portal system that can access the data from multiple databases. Examples are NISbase, which links 8 aquatic non-native species databases, and the Ocean Biogeographic Information System (OBIS), which provides a gateway to over 200 data sets containing information on marine species (Table 1).

Although the current systems provide access to data not easily obtained even a decade ago, continued development and expansion of these systems will enhance their future capabilities. One limitation of many of the current aquatic information systems is that they only include species considered non-native to a particular region. As biological information systems evolve, it is likely that more of them will begin to incorporate native species or become part of distributed systems that include natives. Most of the data sources in Table 1 provide at least basic habitat requirements and some provide information on life-history characteristics. In most cases, however, these data are presented in a narrative form or in tables that cannot be easily queried, which makes it difficult to extract data for multiple species or from multiple sources. Development of a standardized classification of key habitat requirements and life-history characteristics would simplify extraction of these data and enhance the usability of the existing storehouse of natural-history information.

Only a few of the information sources in Table 1 provide physiological tolerances. Because physiological tolerances can be used to generate at least an approximate "climate envelope" for a species, an increased effort in synthesizing thermal and salinity tolerances seems warranted. Rather than attempting to capture exact thermal

Table 1. Examples of existing biological information systems for the United States.

National, regional and quantitative databases	*Spatial coverage and resolution*	*Taxa included in database*	*Native or non-native species*	*Abundance data*	*Life history or habitat*[a]	*Source*[b]
National aquatic native and non-native species distributions						
NAS	entire U.S. 6-digit HUC[c]	freshwater, coastal, and estuarine fishes, invertebrates, vascular plants, and algae	non-native	no	life history and habitat (text)	1
NISbase (Web portal)	entire U.S. and Mediterranean, resolution varies by database	freshwater, coastal, and estuarine fishes, invertebrates, vascular plants, and algae	non-native	no	varies by database	2
FishBase	global and site-specific records of occurrence	marine, estuarine, and freshwater fishes	native & non-native	catch statistics	life history and habitat (query)	3
OBIS (Web portal)	global and site-specific records of occurrence	marine fishes and invertebrates	native & non-native	yes (depending on database)	habitat (text)	4
plants	entire United States	vascular plants	native & non-native	no	habitat (text)	5
Regional aquatic native and non-native species distributions						
MarineID	northeastern United States and Atlantic Canada	marine and estuarine invertebrates and algae	non-native	no	habitat (text)	6
NEMESIS	Chesapeake Bay	aquatic and wetland mammals, bird, reptiles, amphibians, fishes, invertebrates, algae, and plants	non-native	no	life history and habitat (query)	7
NIS in Gulf Mexico and South Atlantic	Gulf of Mexico and South Atlantic	viruses, reptiles, birds, mammals, fishes, and aquatic invertebrates	non-native	no	life history and habitat (text)	8
PCEIS	northeast Pacific (Alaska to northern Mexico)	marine and estuarine fishes, invertebrates, algae, and plants	native & non-native	no	habitat (query)	9
Hawaii guides and databases	Hawaii	marine invertebrates and algae	native & non-native	no	life history and habitat (text)	10–13
Quantitative data sources						
EMAP (coastal and surface waters)	coastal = entire United States	coastal: marine and estuarine invertebrates and fishes	native & non-native	yes	habitat (query)	14
	surface waters = great lakes, mid-Atlantic, eastern Lakes, Oregon, Washington	surface waters: freshwater benthic invertebrates, fishes, and zooplankton (depends on location)				
NAWQA	conterminous United States	freshwater fishes, invertebrates, and algae	native & non-native	yes	habitat (query)	15

[a] *Text and query are, respectively, whether the data are presented in narrative descriptions or whether the data be queried by species, habitat, or trait.*

[b] *Sources: 1, Nonindigenous Aquatic Species database (http://nas.er.usgs.gov/); 2, NISbase (http://www.nisbase.org); 3, FishBase (http://www.fishbase.org/search.php); 4, Ocean Biogeographic Information System (www.iobis.org); 5, USDA PLANTS Database (http://plants.usda.gov); 6, MarineID Marine Invader Database (http://www.marineid.org/marine/html/index.html); 7, Chesapeake Bay Introduced Species Database (http://invasions.si.edu/nemesis/chesapeake.html); 8, Non-Native Aquatic Species in the Gulf of Mexico and South Atlantic Regions (http://nis.gsmfc.org/default.php); 9, Pacific Coast Ecosystem Information System (database available from H. L. and D.R.); 10, Introduced Marine Species of Hawaii Guidebook (http://www2.bishopmuseum.org/HBS/invertguide/invertintro.htm); 11, Invasive Marine Algae of Hawai'i (http://www.hawaii.edu/reefalgae/invasive_algae/); 12, ReefWatcher's Field Guide to Alien and Native Hawaiian Marine Algae (http://www.hawaii.edu/reefalgae/natives/sgfieldguide.htm); 13, Invertebrate Zoology Databases (http://www.bishopmuseum.org/research/natsci/invert/databases.html); 14, U.S. EPA's Environmental Monitoring and Assessment Program (http://www.epa.gov/emap/html/data/index.html); 15, USGS National Water Quality Assessment (http://infotrek.er.usgs.gov/traverse/f?p=136:1:4080126102230352::NO).*

[c] *Hydrologic unit code.*

and salinity tolerances from laboratory experiments or field distributions, it will often be adequate to use tolerance classes. Knowledge of temperature ranges for freshwater fishes coarsely categorized into cold- and warm-water thermal guilds is useful for predicting climate-induced changes in the availability of thermally suitable habitat in streams and lakes (Eaton & Scheller 1996; Stefan et al. 2001) and for predicting invasion potential in the Great Lakes (Mandrak 1989). Similarly, salinity classes adequately explain regional invasion patterns for brackish-water species in Europe (Paavola et al. 2005). As with habitat requirements, developing a standardized classification for physiological limits would simplify data extraction for multiple species or from multiple sources.

Another important physiological trait for freshwater species that could be captured is their response to changes in hydrology. For example, life-history characteristics of freshwater fishes are highly predictive of rates of spread in response to past hydrological changes (Olden et al. 2006). Given these types of observations, climate-induced changes to riverine hydrology are likely to influence habitat suitability for both native and nonindigenous species (NIS) and could influence invasiveness (Rahel & Olden 2008). In recent years these traits have been systematically collected for large numbers of freshwater fishes (e.g., Goldstein & Meador 2004), although similar syntheses appear to be lacking for marine and estuarine species.

Environmental Data Layers and Climate-Change Scenarios

The synthesis of environmental data has grown both from advancements in information technology and from the strides in capturing high-resolution data from remote sensing technologies. Table 2 provides sources of environmental data relevant to assessing current conditions and sources for environmental data layers for input into niche models. Additional sources of environmental data at a point scale are the ambient monitoring programs, such as EMAP and NAWQA (Table 1). In addition, environmental data layers for terrestrial vegetation, soil type, and topography that have been used to predict distributions of terrestrial species (e.g., Elith et al. 2006) are available and may be useful in predicting distributions of freshwater and estuarine species.

Projections of future environmental conditions are derived from climate-change scenarios produced with general circulation models (often called global climate models) (Table 3). The climate models listed in Table 3 are only an entrée into a complex and rapidly evolving research area, although the Intergovernmental Panel on Climate Change (IPCC) is the most often-used source for multiple model access and model ensemble runs. The IPCC in its Fourth Assessment Report (2007) uses more than 20 different general circulation models. These models converge fairly well in terms of reproducing 20th century change in temperature, but they are not as consistent in simulating past and future changes in precipitation. Climate models also currently lack the spatial and temporal detail needed to make confident projections of extreme events, such as drought or tropical storms, which can affect species distributions.

Projections from climate models can be directly input into biotic models to predict changes in population distribution or abundance (Fig. 1). For example, niche models can be used to predict changes in distributions in response to climate change (e.g., non-native fishes, Chu et al. 2005; Sharma et al. 2007; terrestrial species, Araújo et al. 2005; Thuiller et al. 2005). When making such predictions, the type and resolution of the environmental data must be consistent with the spatial extent and granularity of the question. Spatial resolutions of projected climatic condition are at a relatively coarse grain compared with the distributions of many species. Most climate models (Table 3) have a spatial resolution of 2° or 3° latitude by 2° or 3° longitude, which translates into 250–600 km. Depending on the question, the appropriate scale for predicting species-specific responses may be orders of magnitudes smaller than the resolution of climate-model outputs. Thus, it will often be necessary to downscale model outputs (e.g., Wood et al. 2004) so that the environmental and biological data layers have consistent spatial resolutions.

Predicting Distribution and Abundance of Species

Niche models to predict the distribution of species on the basis of environmental conditions are increasingly being evaluated as to their accuracy and utility (e.g., Rodriguez et al. 2007), and such models can serve several functions in assessment of the effects of climate change (Fig. 1). First, they can be used to predict the potential spread of existing invasive species under current environmental conditions. Second, model predictions can be used to project current distributions of rare or endangered native species whose actual distributions are often poorly known because they are missed in standard monitoring programs. Lastly, these models can be used to predict changes in the distribution or abundance of native or non-native species under altered climate conditions, including the potential for new invaders to become established.

Most recent efforts predict the potential geographic distributions of invaders with models such as the Genetic Algorithm for Rule-set Production (GARP, http://nhm.ku.edu/desktopgarp/index.html) that use occurrence data (Peterson 2003). These types of models have been used for several aquatic species, such as the zebra mussel (*Dreissena polymorpha*) (Drake & Lodge 2006) and rainbow smelt (*Osmerus mordax*) (Mercado-Silva et al.

Table 2. Examples of sources for aquatic, environmental, and land-use data layers.

Environmental attribute	Spatial extent and granularity	Temporal extent and granularity	Sources[a]
Climatic			
climate data sets from U.S. state, local, federal sources, including surface temperature, precipitation, growing degree days	global, national, regional and local; spatial resolution varies	hourly to annual/decadal summaries for 8000 + U.S. stations and 4000+ stations in other countries	1, 2, 3
Oceanic and estuarine			
sea surface temperature	global oceanic and U.S. coastal waters; resolution varies (1.1 km finest)	varies (3 h finest resolution)	4
salinity at selected buoys w/ air and sea surface temperatures	near-coastal sites and selected estuaries across the United States, Great Lakes, oceanic sites globally	minute to daily	5
chlorophyll-a and turbidity	entire U.S. coast; resolution varies, approx. from 1 km	4–10 images per day	6
wetland classification of estuarine and freshwater habitats	entire U.S. 0.25- to 5- acre minimum mapping unit	varies (1970s to present)	7
estuarine and watershed drainage areas with estuarine-scale environmental attributes	138 major estuaries in conterminous U.S. estuary and watershed scales	current	8
Freshwater and hydrologic			
stream, lake, pond location, and stream order	entire U.S. 1:100,000K or 1:24,000K or better	current	9
time series of stream levels, streamflow, reservoir and lake levels, surface-water quality, and rainfall	entire U.S. real-time surface water data at 8000+ sites and daily data at 24,000 + sites	length of record varies; minutes to annual	10
historical streamflow records, 1874–1988	entire United States at 1600 + specific stream sites	daily, monthly, and annual mean discharge	11
Landscape and population			
land-use classes and impervious surfaces	conterminous United States with AK and HI planned; 30-m pixel	1992 and 2001	12
population and population change	entire U.S. data available at various scales, including census block, 8-digit HUC,[b] and by NOAA's EDAs[c]	1970–2000 by decade	13, 14

[a] *Sources: 1, National Climatic Data Center (http://www5.ncdc.noaa.gov/cgi-bin/script/webcat.pl?action=ALL); 2, Daily Surface Weather and Climatological Summaries (http://www.daymet.org); 3, Climate Source (PRISM) (http://www.climatesource.com/); 4, NOAA CoastWatch (http://coastwatch.noaa.gov/cw_dataprod_sst.html); 5, National Data Buoy Center (http://www.ndbc.noaa.gov/); 6, NOAA CoastWatch (http://coastwatch.noaa.gov/cw_dataprod_color.html); 7, National Wetland Inventory (http://www.fws.gov/nwi); 8, NOAA's National Coastal Assessment and Data Synthesis (http://coastalgeospatial.noaa.gov/); 9, National Hydrological Dataset (http://nhd.usgs.gov/); 10, National Water Information System (http://waterdata.usgs.gov/nwis/sw); 11, Hydro-Climatic Data Network (http://pubs.usgs.gov/wri/wri934076/1st_page.html); 12, National Land Cover Database – 2001 (http://www.mrlc.gov/index.asp); 13, U.S. Census (http://www.census.gov/); 14, NOAA's Coastal Geospatial Data Project (http://marineeconomics.noaa.gov/socioeconomics/).*

[b] *Hydrologic unit code.*

[c] *Estuarine drainage area.*

2006). An advantage of models that rely only on presence data is that it is possible to use records from museums, herbariums, or other nonsystematic collections. In a recent comparison, 16 biotic modeling approaches predicated on presence-only data were evaluated across 6 regions of the world (Elith et al. 2006). Although no aquatic species were included, these authors found that the models were sufficiently accurate for conservation planning in most cases. They also found that some of the newer approaches, such as maximum entropy models (Maxent, Phillips et al. 2006) and boosted regression trees (Leathwick et al. 2006*a*), outperformed approaches such as GARP. Nevertheless, another study found that GARP may outperform Maxent under some conditions (Peterson et al. 2007), indicating the need for further model comparisons. When abundance data are available, regression-based approaches to niche modeling, such as MARS (Leathwick et al. 2006*b*) and nonparametric multiplicative regressions (NPMR) (McCune 2006), can predict changes in abundance and distribution. For well-studied species, an alternative approach to niche models derived from field occurrences are models predicated on life-history traits or physiological characteristics. Such an approach has been used to predict changes in ranges and rates of spread (Olden et al. 2006).

Although the ongoing development of niche models is encouraging, a number of issues remain. The biotic and environmental data need to be harmonized in terms of

Table 3. Examples of sources for greenhouse gas-emission scenarios for climate-change models and other climate-related data sets and model results.

Environmental attributes	*Spatial extent and resolution*	*Temporal resolution and extent*	*Sources**
Emission scenarios			
scenarios of future development and greenhouse gas emissions	global	to 2100	1
global climate data sets & projections			
mean monthly surface air temperature and precipitation for global land areas, excluding Antarctica	global and regional; multivariate 0.5° latitude × 0.5° longitude resolution	1850–2300, depending on model and variable	2
surface air temperature; daily minimum surface air temperature; total precipitation rate; surface runoff; surface specific humidity	global, down scaleable to regions generally gridded at 0.5° latitude × 0.5° longitude (horizontal resolution of 250–600 km)	subdaily predictions with extrapolations out to 2100	3
mean global sea level under different emission scenarios from atmosphere-ocean general circulation models simulations	global	generally 1900–2100	4
Environmental simulation models			
30 software packages to predict streamflow, sediment discharge, and other water-quality parameters	local to watershed	temporal resolution varies by model	5

**Sources: 1, IPCC Data Distribution Center (http://www.grida.no/climate/ipcc/emission/); 2, WCRP CMIP3 Multi-Model Dataset (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php); 3, IPCC Data Distribution Center (http://www-pcmdi.llnl.gov/projects/cmip/index.php); 4, IPCC Data Distribution Center (http://cera-www.dkrz.de/IPCC_DDC/IS92a/sea_level.html); 5, USGS Surface Water Software (http://water.usgs.gov/software/surface_water.html).*

scale, resolution, and GIS map projection. In addition, many important aquatic environmental parameters (e.g., sediment size) may not be available as a continuous data layer, which is required for mapping the model predictions onto unsampled areas. When continuous environmental data layers are lacking, niche models can be derived from point data with regression approaches such as NPMR. These models can be used to predict the probability of occurrence or abundance at specific locations where the environmental parameters are available, although continuous environmental data layers would still be needed to generate maps of a species distribution. Regardless of the modeling approach used, the results need to be critically evaluated. Models used to project population trends should be validated by assessing their accuracy in predicting existing spatial distributions. Nevertheless, even biotic models with a high accuracy under current environmental conditions may not perform well when extrapolating to climatic conditions or locations outside those used to develop the model (Araújo et al. 2005; Elith et al. 2006). Because of these complexities, it is critical to have a thorough understanding of the species being modeled and the models (Heikkinen et al. 2006).

Integration of Information Systems, Monitoring, and Modeling

A final challenge is the integration of the components needed to predict the combined effects of climate change and invasive species. The framework laid out in Fig. 1 presents one possible approach to interconnecting monitoring, information-systems, and modeling components. Some progress has been made in this arena; integrated systems exist or are under development that contain a few to many of the components in Fig. 1. One system primarily used for terrestrial species is the Global Organism Detection and Monitoring system (GODM; Graham et al. 2007). The GODM provides species distribution and abundance data from multiple users and includes attributes of their habitats for spatial modeling of current and potential distributions (www.NIISS.org). For marine environments, modeling tools are available in FishBase and OBIS, both of which dynamically link to Kansas Geological Survey Mapper (KGSMapper, http://drysdale.kgs.ku.edu/website/Specimen_Mapper/; Guinotte et al. 2006).

Although these sites represent major accomplishments, additional developments could enhance their scientific and management utility. One avenue would be to incorporate the recently developed modeling approaches. OpenModeler (http://openmodeller.sourceforge.net) provides access to 8 modeling algorithms, including GARP. Inclusion of newer approaches, such as Maxent or boosted regression tress, would promote comparisons of modeling techniques across a range of species and ecosystems. Another area of improvement would be to develop Web portal systems that allow users to extract the global distribution of a species with native and non-native ranges identified. Assuming the corresponding environmental data layers are available, this would allow identification of potential new invaders with "environmental matching" (e.g., Gollasch 2007) or the comparison of predictions of species distributions on the basis of native versus invaded ranges (Loo et al. 2007). Lastly, continuous environmental data layers are not widely available for a number of basic parameters, such as sediment type or estuarine salinity gradients. Generation and incorporation of these data layers into these Web portal systems would allow development of niche models for a greater range of species and ecosystem types.

The process outlined in Fig. 1 needs to undergo rigorous validation with existing and new, independent data. Today's management decisions require projections of aquatic population trends over a 20- to 50-year horizon and over large areas not presently occupied by the target species. The complexity of this endeavor requires that the uncertainties be presented along with the predictions. As our knowledge and understanding expands, the goal is for the predictions to outweigh the uncertainties.

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