TECHNICAL REFERENCE DOCUMENT

DEVELOP THE CAPACITY TO MAKE ECOLOGICAL FORECASTS

1. Introduction

Ecological forecasts offer decision makers estimates of ecological outcomes given specific natural events, and/or management or policy options. In ecological forecasts, projections of the future state of ecosystems, and ecosystem services and/or natural capital are derived from specific scenarios of future land and human resource use, natural events, climate change, and policy actions. Society benefits from and depends on a wide range of ecological services including purification of air and water, mitigation of droughts and floods, generation and preservation of soils and renewal of their fertility, detoxification and decomposition of wastes, pollination of crops and natural vegetation, dispersal of seeds, cycling and movement of nutrients, control of many agricultural pests, maintenance of biological diversity, protection of coastal shores from erosion, and provision of aesthetic beauty and opportunities for recreation (ESA 1997). Alterations of ecosystem processes can dramatically affect important ecological services and the quality and standard of life, including local and regional economies (Loucks and Gorman 2004). Ecological forecasting is critical in understanding potential changes in ecological services, before they happen, and are critical in developing strategies to off-set or avoid catastrophic losses of services.

Ecological forecasting often involves the actual prediction of ecological outcomes based on a combination of biophysical observation data and models (Clark et. al. 2001). The primary goal of ecological forecasting is to predict the effects of biological, chemical, physical, and human induced pressures on ecosystems and their components at community, landscape, watershed, regional, and national spatial scales and over a range of temporal scales, given a certain set of assumptions (CENR 2001). Examples of such pressures include extreme natural events, climate change, land and resource use, pollution, invasive species, and human/wildlife diseases. Once certain cause-effect relationships are established, the goal then is to develop management strategies and options to reverse declining trends, reduce risks, and to protect important ecological resources and associated processes (Baker et. al. 2004, Bradley and Smith 2004, Fitz et. al. 2004). Such an approach is critical to the concept of sustainable development (Reid et. al. 2002, Valette-Silver and Scavia 2003, NASA 2004).

Ecological forecasting is an integral part of many of the goals of other societal themes as described in this chapter, but especially those related to: (1) protecting and managing terrestrial, coastal, and marine ecosystems, (2) understanding, assessing, and mitigating climate change impacts, (3) identifying options for sustainable agriculture and reversing and combating land degradation and desertification, (4) promoting human health and well being, (5) protecting water resources, and (6) understanding, monitoring, and preserving biological diversity. Forecasting is fundamental in understanding what needs to be done to avoid human and environmental disasters and to promote sustainable development. In this regard, forecasting plays an important role in early warning and risk assessment. For example, NOAA integrates *in situ* and remotely sensed measurements with models to provide early warning and nowcasts for sea nettles, pink shrimp harvest, and coral bleaching (http://www.nos.noaa.gov/topics/coasts/ecoforecasting/welcome.html). Other examples from the physical sciences include observation and model-based short-term weather forecasts, which have been available for several decades, and the more recent and longer term predictions of climate phenomena, such as El Nino/Southern Oscillation (ENSO) events (McCade et. al. 2004).

Generally, managers, stakeholders, and decision makers require two types of ecological forecasts: (1) short-term forecasts (e.g., 3-24 months) and (2) longer-term forecasts (e.g., 5-50 years). Short-term forecasts give stakeholders early warning of events and conditions that might affect key economic activities and human safety. For example, managers in the Gulf of Mexico use NOAA forecasts of harmful algal blooms to determine which shellfish habitats might be at greatest risk. These near-real time data are used by managers to help target areas that need more detailed data collection (http://www.csc.noaa.gov/crs/habf/bulletin.html). Similarly, integration of real- and near-real time climate and biophysical data with historical and current patterns of vegetation productivity (net primary production or NPP), are being used to target areas of greatest risk of crop failure (Reynolds et. al. 2000), as well as predicting patterns of greenness and departure of greenness from historical patterns (Running et. al. 2004). Early warning of the former risks helps farmers develop strategies to reduce crop loss and financial hardship (Kastens et. al. 2001, de Beurs et. al. 2004), whereas early warning of the later is being used to help nomadic farmers in Africa determine where to migrate (Hutchinson 2001, Herrmann and Hutchinson 2004). Other potential uses of NPP estimates and forecasts might include (1) when to move grazing animals to different pastures (to reduce impact of grazing on climate-stressed lands), (2) identification of streams at increasing risk to erosion and sediment and nutrient loading, (3) areas vulnerable to catastrophic wildfires, and (4) areas vulnerable to invasive species (Running et. al. 2004). Longer-term forecasting is more often used to address broad policy and management issues of Federal agencies, as well as to develop environmental planning options at local and watershed scales (Baker et. al. 2004).

Ecological forecasting can be lumped into two general approaches. The first general approach involves an attempt to predict future conditions of ecological goods (products) and services (processes and functions affecting environmental condition) with known levels of confidence (Clark et. al. 2001). This approach often uses spatially explicit models derived from historical change, which are then applied to the future, with the general assumption that future changes will approximate historical changes (Hall and Fagre 2003, Matheny and Endres 2003, Jackson et. al. 2004). In some cases, these models are developed by evaluating changes in the ecological endpoint of interest across biophysical gradients. This is often referred to as trading space for time. For example, Galbraith et. al. (2003) developed habitat models for shorebirds based on current patterns of feeding habitats. They then used sea level change scenarios to forecast how shorebird habitat might change by the years 2050 and 2100. Stock sizes of shrimp can be forecast on the basis of estuarine water temperature (Hettler 1992). Menhaden recruitment is known to be correlated with river flow (Govoni 1997).

The second general approach involves the development and use of spatially distributed models, but unlike the first general approach, does not try to predict how the future will change but rather to identify a range of alternative environmental futures (White et. al. 1997, Monaco et. al. , 2003, Baker et. al. 2004, Hulse et. al. 2004, Kepner et. al. 2004) using a set of future scenarios derived from expected or plausible changes (Reid et. al. 2002, Martin 2003, Neale et. al. 2003, Scavia et. al. 2003, Aycrigg et. al. 2004), or through extensive interactions with the stakeholders. Similar to predictive approaches, spatially explicit landscape models used in scenario assessments are often derived by evaluating current patterns in spatial variability. For example, Stohlgren et. al. (2003) modeled vulnerability to invasive species spread by quantifying relationships between invasive species richness and spatial variation in certain biophysical parameters, including soil texture and chemistry, topographic position, elevation, slope, aspect, greenness indices, and land use data. From this empirical model it was then possible to evaluate potential vulnerability of invasive species establishment across the entire landscape. Peterson et. al. (2003) used a similar approach to model the spread of emerging diseases, plant and animal pests, invasive species of plants and animals and their effects on natural resources, and agricultural crops and human populations. Fonseca et. al. (2002) have quantified the connections between coastal morphology and wave regimes with the ability of seagrass meadows to recover from man-made or natural destruction. Stumpf et a.l (2003) have developed an operational forecast for landfalls of harmful algal blooms based on the remote sensing of chlorophyll. Coral reef bleaching has been found to be correlated with episodic peaks in sea surface temperature (Mumby et. al. , 2004). Empirical models are commonly used to extend estimates made from sparsely collected field samples to broader geographic regions (Jones et. al. 2001).

Reid et. al. (2002) argue that forecasting differs from prediction in that "a forecast is the best estimate from a particular method, model, or individual. The public and decision makers understand that a forecast may or may not turn out to be true." In fact, it is imperative for ecological forecasts to be associated with estimates of uncertainty or "error bars" so that decision makers using them have information as to the likelihood of a given forecast.

Forecasting species and environmental changes represent a formidable challenge in science, in that the basic mathematics and modeling approaches for such forecasting are in their infancy. Ecosystem complexity and scaling issues increase error and uncertainty in ecological forecasting. However, ecosystem forecasting is critical if one is to reduce environmental threats and sustain a wide range of ecological services upon which humankind depends.

2. User Requirements

Ecological forecasting requires the acquisition of a wide range of environmental data, as well as development of models. However, the amount of environmental data and the number and complexity of models needed to conduct ecological forecasting varies tremendously, depending on the type of ecosystem and the set of specific forecasting questions being addressed (for example, short-term versus long-term forecasts). The types of questions being asked and the goals of the forecasting activity influence the number of spatial and temporal scales that need to be addressed; these in turn affect the magnitude and complexity of data and model needs (Costanza and Voinov

2004). For example, forecasting changes in run-off and sediment as a function of land cover change scenarios developed by stakeholders is a relatively straight forward process involving use of digital soil erosivity data, land cover, precipitation maps, and a spatially distributed hydrologic model (Kepner et al. 2004). In this case, the alternative future landscapes result in different soil exposure and land cover composition and patterns, which result in different sediment and run-off predictions from the hydrologic model. Alternatively, forecasting the responses of species to future environmental scenarios, or changes in ecological functions at relatively fine scales (e.g., within a 30 x 30 meter pixel), usually involve complex and dynamic models and data because of greater complexity in horizontal and vertical scaling functions (Martin 2003, Monaco and Livingston 2003, Rastetter et al. 2003, Costanza and Voinov 2004, Deal et al. 2004). Therefore, it is very important to identify a set of assessment questions in determining the specific requirements for ecological forecasting.

Table 1 provides examples of the types of questions that might be asked in association with ecological forecasting. The examples given are, in no way, a complete list of questions that could be asked. These questions also could address current and future environmental threats associated with: (1) human population growth and demand for resources, (2) harmful invasive plants, animals, and diseases, (3) a wide range of contaminants, (4) altered disturbance regimes and other natural processes, and (5) other factors that could potentially affect fundamental ecological services. Assessment questions also reflect the need for short-term and long-term ecological forecasting.

Table 1. Assessment questions related to ecological forecasting

Short-term Forecasts (3-24 months)
Given current and near-term biophysical and climatic conditions, and information on historical patterns of invasions and occurrence, which areas are most vulnerable to invasive species spread? Which areas are not likely to experience invasive species establishment and spread over the next 2 years?
Given current and near-term projections of biophysical and climate conditions, and information on historical patterns of occurrence, which forests and woodlands are most likely to experience catastrophic fires over the next fire season? Which areas are likely to be the least vulnerable over the next 2 years?
Given current and near-term projections of biophysical and climate conditions, and information on historical patterns (spatial and temporal) of productivity, which areas in the mid-west are likely to experience significant levels of crop failures? Which areas are likely to produce normal or above average yields?
Given spatial patterns of ecosystem productivity (Net Primary Production or NPP), recent patterns of drought, air pollution, and other biophysical conditions, which forests are most vulnerable to disease outbreaks?
Given current and near-term projections of biophysical and climate conditions, which coastal waters are likely to experience harmful algal blooms? Once established, what is the spatial pattern of further spread?

Which areas are likely to experience drought? What freshwater biota are most vulnerable to extended drought? What freshwater endangered species are threatened by extended drought?
Given measurements of salinity and water temperature, which areas of the Chesapeake Bay are likely to experience high occurrences of sea nettles? What is the spatial overlap between areas that are likely to have high abundances of sea nettles and beaches where people frequently swim?
How do broad-scale, seasonal to interannual climatic events (e.g., ENSO, NAO, etc) influence the productivity of selected coastal or pelagic fisheries
Given winter water temperatures, is pink shrimp harvest likely to be lower or higher than the average the following year?
Given spatial patterns of ecosystem productivity (NPP) which flyways are likely to experience higher mortality rates of neotropical migrant birds? Which areas are likely to experience reduced reproductive success? Which areas are likely to have normal or above average reproductive success?
Long-term Forecasts (5 – 50 years)
Under different scenarios of global climate change, which terrestrial ecosystems are likely to experience greater intensity and frequency of catastrophic fires? What is the likelihood that these ecosystems will convert to a less desirable state? Which areas will be at greatest risk to loss of property and human lives due to changes in key ecosystem attributes such as water infiltration capacity or fuel loading? Which coastal areas will receive more runoff and how will they respond?
Under difference scenarios of land use, what changes in biodiversity are likely? What species may have their range expanded > 25%? What species may have their range diminished >25%, or even put on a path of extinction
Under different climate change or land use scenarios, what areas are most vulnerable to increases in occurrence of invasive species?
Under different climate change or land use scenarios, what are the consequences and vulnerabilities on rare and endangered species?
What are the long-term effects of tropical deforestation on climate, wildlife, and human livability?
Under different climate change and urban sprawl scenarios, which forests are likely to experience significant declines in productivity? What will be the impact on the forest products economy? What are the spatial relationships between changes in forest productivity and species diversity?
Under different scenarios of urbanization and development (increases in impervious surfaces), which river basins and streams are likely to experience high rates of loss of aquatic and riparian biological diversity?
Which coral reefs are the more vulnerable to bleaching from spikes in sea surface temperature and will they recover?
Which marine, coastal, and estuarine ecosystems are at greatest risk given scenarios of future environmental change? Which changes in future environments will have the biggest negative impact on these resources? What policies and/or management scenarios would best reduce future risks to these

resources? If left unmitigated, what would be the economic consequences of future environmental change?
Under different exploitation scenarios, which stocks of living marine resources will be most vulnerable to over fishing, and how will marine ecosystems be affected?
Which coastal areas are the more vulnerable to sea level rise and how will different types of lowlands respond?
How will green technologies offset ecological and hydrologic changes associated with urbanization, desertification, and/or climate change?
What Best Management Practices (BMPs) need to be developed or implemented to off-set climate- and urbanization-associated changes? What is the optimal spatial distribution of BMPs related to mitigating impacts of climate change and urbanization? How does this vary among communities in different biophysical settings? What BMPs are needed to protect aquatic resources? What BMPs are needed to protect terrestrial resources?
How effective are our land conservation programs likely to be in protecting biological diversity given specific scenarios for global climate, urbanization, and land degradation? What alternative land conservation strategies might better protect biological diversity in the face of scenarios of future environmental change? What management practices might be conducted in the matrix surrounding local 'hot spots' to promote biodiversity?
What management practices can best be utilized to reduce catastrophic forest fires, while maintaining the fire-dependent or fire-promoted communities over much of the nation's forestlands?
What policies and/or management practices can be adopted to reduce the loss of productive agricultural lands? Where are the agricultural lands that are at greatest risk of being converted to non-agricultural uses? Given different alternative future scenarios, what is the economic and social impact of agricultural lands converted to other uses?

Many organizations and agencies need Earth observation data and models to forecast changes in important ecological resources and processes. These include city, county, and watershed organizations that are trying to evaluate options for smart growth (Voinov et al. 2004, Berger and Bolte 2004), as well as initiatives to evaluate the vulnerability of ecological resources and processes to near-term environmental conditions, as well as longer-term degradation (Valette-Silver and Scavia 2003, Bradley and Smith 2004, Claggett et al. 2004). Other users will be managers of federal, state, and tribal lands and waters charged with maintaining the viability of these areas and complying with the mandates of relevant environmental legislation, such as the Clean Water Act, Endangered Species Act, and National Environmental Policy Act.

A need for shorter-term forecasting (daily to monthly) in a direct or stochastic sense at the local level where many decisions are made or future scenarios are evaluated is also sorely needed. These forecasts should account for perturbations from large-scale atmospheric forcings (e.g. ENSO) which coupled ocean-climate models can now predict with greater accuracy. Current weather generators, which are commonly used to provide input to management and ecological models could be improved by including teleconnection perturbations (Woolhiser, et al. 1993).

Incorporation of the ENSO signal using the Southern Oscillation Index (SOI) into daily precipitation models has significantly improved these models' capacity to simulate sequences of daily precipitation in the southwest by increasing the variation of monthly and annual totals of precipitation occurrence and amount. It has been shown that a lead time exists between the Southern Oscillation Index and daily precipitation in this region. This information can be exploited to provide conditional simulations of near-future precipitation, valuable for land and water resource managers. These techniques, with long-term (~30 years) rain and temperature observations, can be used to geographically map the influence large-scale atmospheric forcing by statistically indicating whether the forcing as measured by some index or sea surface temperature:

1) significantly influences observed rainfall/temperature at the gauge and for which months;
2) the lead-time between the index and the observations (see the NRCS GEM effort at http://www.wcc.nrcs.usda.gov/climate/gem.html).

Finally, a comprehensive forecasting system is needed to address the broader issue of bioinvasions, bioterrorism, and bioscecurity (Meyerson and Reaser 2003).

Because of the diverse needs for forecasting at a range of scales, there will be a comprehensive and wide range of Earth observation data requirements. However, these observations are likely to fall out into two general classes: spatially continuous biophysical data derived from remote sensing and other sources, and field or site data on specific ecological and hydrologic processes and/or state variables. Site data are needed to measure and estimate important ecological and hydrologic variables (across space and time) which then can be related empirically or via process, or mechanistic models, to spatially continuous biophysical data (Van Rompaey and Govers 2002, Kratz et al. 2003, Rastetter et al. 2003). Site data also are needed to calibrate ecological process models. Biophysical data provide an extrapolation framework to estimate conditions over broader areas, and to areas not sampled (Costanza and Voinov 2004). In addition, they allow for the detection, observation, and modeling of ecological phenomena occurring at landscape scales and beyond. Using concepts of ecological hierarchy theory (Allen and Starr 1982, O'Neill et al. 1986) biophysical and biogeochemical data can also be used to construct ecosystem classification approaches to reduce variability predictions in responses of ecosystems to perturbations. Table 2 provides an initial list of the Earth observations that are required to conduct enhanced ecological forecasting in the United States.

Table 2. General list of Earth observation needs and capabilities

Digital national land cover at 30 meter resolution from the mid-1980s to the present day (to measure and estimate a number of important landscape pattern and process factors affecting ecological condition and changes and to improve forecasts based on future land cover change from urbanization, etc.)
A national, consistent map of vegetation types, classified to the highest spatial and attribute level possible. (the FGDC vegetation classification, largely built by NatureServe and Ecological Society of America)
National soils database, including information on soil texture (SURRGO) (to estimate soil loss, erosion, and nutrient export at a range of spatial scales; higher resolution soil moisture information is a key observational parameter for future development)
A national, high resolution (<30m) map of long-term soil moisture availability (critical for vegetation mapping, moisture availability and storage, successional pathways development) (see Iverson et al. 1997 for an example: the Integrated Moisture Index)
10 meters digital elevation model data except in coastal regions where 0.5 meter data are needed (to estimate and model surface flow, run-off, and other critical processes related to water movement)
Precipitation/climate data at 1km resolution or less on hourly time-scales (to estimate surface flows, surface temperature, atmospheric temperature, evapotranspiration, soil erosion, and other important ecological functions that are linked to climate)
Enhanced stream hydrography data (to improve estimates of the spatial distribution of perennial stream flow and connectivity among aquatic habitats and biota
Increased number of continuous flow monitors for streams and other surface water (to improve models linking landscape condition, like impervious surface changes, to surface water chemistry, physical habitat, and aquatic biological condition)
Detailed locational information on water resources use (drinking water, industry, agriculture, power), extraction (irrigation, public, private), source (surface water, groundwater), management (permits, allocation, transfers, drought), and infrastructure (dam, impoundment, levee) to evaluate potential impacts and stress to hydrological processes and aquatic resources
Digital data on vegetation canopy structure and height (to improve modeling of suitable habitat for animal species; to improve estimates of biomass and leaf area indices that are important input variables in ecological processes models)
Data on physiological characteristics of vegetation (by species, mostly obtained via controlled, ground-based instrumentation), critical for modeling storage and allocation of carbon and nitrogen
Increased number of fixed and remote monitoring stations that measure fundamental ecological processes including carbon flux, energy flux, solar radiation, evapotranspiration, and nitrogen flux (to improve ecological process models and extrapolations to stand/patch and landscape scales)
Increased number of fixed monitoring stations that measure atmospheric deposition of sulfate, nitrogen, mercury, and other air toxics know to effect terrestrial and aquatic

ecosystem (to improve models and estimates of the impacts of future emissions policies and regulations on ecosystems)
An increased network of scientists collecting species- and genotype-level data related to population trends and environmental factors controlling the species. A fine-scale network of data collection so that range boundaries, by species, can be reliably detected and mapped. (for evaluation of range shifts under changing conditions, critical data for development and validation of models)
Increased number of fixed monitoring sites that measure both terrestrial and aquatic species richness, species diversity, genetic (molecular-based) diversity, and other measures of biological integrity (to improve habitat models of species over a range of spatial scales and to improve forecasts of how changes in biophysical properties affect spatial patterns of diversity, etc
Animal inventories (biodiversity and invasive species) on land, in river and lakes, and at sea
Direct measures, through remote sensing, of ecological variables related to key processes in ecological process models, including but not limited to greenness, net primary productivity, leaf area index, evapotranspiration, and phenology. Hyperspectral instruments may hold particular promise for some of these measures
Remote detection of a variety of key variables for marine ecosystems including: ocean color for the detection of chlorophyll-a concentrations at 1km resolution or better, sea surface temperature at 1km resolution or better, ocean wind speed and direction at 25km resolution or finer, ocean topography, and sea surface salinity (to estimate marine primary productivity, monitor sea surface circulation – a vital element in the dispersal of larvae and other propagules, track interannual climate events, improve understanding of marine food webs, locate ocean fronts rich in higher trophic level organisms, etc.)
Higher spatial and temporal resolution data on stream and surface water temperatures via deployment of automated or remote monitoring devices (to improve estimates of stream temperature ranges that affect key aquatic species, including salmon)
Detailed locational information on human population demographics, road and improvement infrastructure, pesticide and other chemical application, emission and effluent permits and inventories, resource uses (e.g., timber extraction, fishing, and agriculture), and other human related activities (to improve models relating a range of human related stresses to ecological resources and processes)
Detailed locational information on the type and date of Best Management Practices, habitat improvements, and other conservation actions (to improve our understanding about the effectiveness of improvements in maintaining and protecting ecological functions and biological diversity)
Maps of fuels at 30 m resolution. (needed for prediction potential catastrophic fires as well as habitat suitability modeling)
Data on the magnitude and distribution of disturbance agents (e.g., fires, hurricanes, tornadoes, ice storms, pest outbreaks, pathogen outbreaks) that might affect ecosystem structure and function over large areas (to improve evaluation of forecasting the impact of major disturbances on ecological resources and associated processes)
A consistent, fine-scale database on land-use history, predating the Landsat era. Air

photos from the 1930s to map and digitize. Before the 1930s there are maps and observations that can be used to put together these ecological legacy maps. The General Land Office records provide good data for a large section of the country and need to be consistently mapped as well.
A wide range of socio-economic data (e.g., cadastral data, average income levels, consumption preferences) to evaluate relationships between human behavior and fundamental ecological processes (to improve ecological forecasting based on alternative future economic and social conditions)
Finer-scale data of all biological, ecological, chemical, and physical data described above (to improve models and ecological forecasting at community and local scales)
Data on the spatial distribution of light pollution (intensity)
Bathymetry of coastal waters

3. Existing Capabilities and Commonalities

Remotely-Sensed Spatial Data

A number of currently available geospatial data sets are used for observations, monitoring, and ecological modeling that also have relevance to ecological forecasting (Kerr and Ostrovsky 2003, Turner et al. 2003).

Geodetically accurate global data sets of Landsat satellite imagery from 3 epochs (the 1970s at 80 meter resolution, circa 1990 at 30 meter resolution, and circa 2000 at 30 meter resolution) are now becoming available from the Earth Resources Observation System (EROS) Data Center (EDC) (Tucker et al. 2004). These data sets constitute a unique record of land-surface state over the past 30 years. National land cover (30 meter resolution) from the early 1990s is available for the lower 48 United States through the EDC and these data have been used in a number of alternative futures assessments (see Wickham et al. 2002, Kepner et al. 2004, Claggett et al. 2004). Currently, a similar digital database is in development that is based on Landsat 7 data from the early 2000s, but it will also include digital coverages of impervious surface and tree canopy density. The addition of impervious surface estimates and tree canopy density will improve a number of ecological and hydrological models, which in turn should improve forecasting capability. The current estimate for the completion of these new digital databases is 2006.

The Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensors provide multi-spectral data at high temporal frequency (in many cases on a daily basis) and these data have been important in deriving important ecological variables linked to both terrestrial and marine ecological processes. These variables include: vegetation indices, land cover, and sea surface temperature from both AVHRR and MODIS and leaf area index and fractional photosynthetically active radiation (FPAR), evapotranspiration, net photosynthesis and primary productivity, land surface temperature and emissivity, fires and burning biomass, land cover change, vegetation cover conversion, snow cover, sea ice cover, ocean chlorophyll-a concentration, ocean chlorophyll fluorescence, ocean primary productivity, coccolith concentration, marine organic matter concentration, and cloud products from MODIS (for a list of MODIS products please see (http://modis.gsfc.nasa.gov/data/dataproducts.html).

Because of their temporal resolution, these sensors are able to determine spectral patterns of greenness, which can then be used to help in the identification of plant species composition and stress. Additionally, MODIS provides a set of spectral vegetation bands at 250 meter and 500 meter spatial resolutions, providing higher resolution imagery for several of the land feature products useful in ecological modeling. The SeaWiFS (Sea-viewing Wide Field of View Sensor) satellite sensor is used to evaluate phytoplankton and chlorophyll distributions in the world's oceans and provides one of the key data elements needed to monitor harmful algal blooms (HAB). NOAA integrates these data with wind speed and direction data to produce its HAB Bulletin. The Bulletin, which provides near-real time information on HAB, provides timely information to the management community in the Gulf of Mexico during a bloom event (http://ccmaserver.nos.noaa.gov/rsd/products.html).

There has been considerable use of data from satellite radars [e.g., RADARSAT (operational radar satellite that is owned and operated by Canada) and JERS-1 (Japanese Earth Resources Satellite)] and airborne radar systems to assess surface roughness, subsidence, three-dimensional aspects of vegetation canopies, biomass, and wetland extent, especially where these canopies prevent accurate estimates of some of these environmental variables from Landsat and other optical satellite sensors. Radars are sensors that transmit their own pulses of electromagnetic radiation to the surface and then record the radiation returning or "bouncing back" to the sensor. At certain wavelengths, these so-called "active" sensors have the added benefit of being able to view through clouds and even vegetation, both day and night. Many important aspects of habitat suitability relate to its structure and complexity, parameters that lend themselves particularly well to this type of remote sensing. In addition to habitat structure, radars are also quite proficient at detecting water (and topography) under a vegetation canopy and have proved useful at mapping wetlands, whether permanently or seasonally inundated. A SAR (Synthetic Aperture Radar) satellite-based sensor provides important information on marine environments, including oil-spills, ocean water masses, winds, and fronts. However, the U.S. currently does not have a SAR sensor on any of its satellite platforms.

Laser systems, known as LIDARS (Light Detection and Ranging), represent another active sensing technology that holds much promise for the remote detection of vegetation structure and complexity, as well as biomass. LIDAR data can provide fine-scale estimates of vegetation canopy structure and elevation profiles, which are important input variables in ecological and hydrological process models as applied to relatively small areas (e.g., within floodplains to evaluate surface flow and in coastal regions where finer-scale digital elevation data are needed). However, to date, vegetation LIDAR sensors have generally flown on airplanes, making the data relatively expensive to acquire for very large area applications (e.g., regional, multi-state, national). Nonetheless, they do provide data at the local scales for many ecological studies and can also serve as bridging data sets between such finer scales and broader landscape or regional scales. However, LIDAR data are beginning to be collected over entire states (e.g., Conneticut) and countries (e.g., Switzerland). In a coastal (and riverine) context, LIDARs provide high-resolution bathymetry data, as well as information on coral reefs. The integration of LIDAR (for elevation data) and spectral/hyperspectral sensors also shows great promise.

Although there is considerable research on the use of hyperspectral imagery to detect relatively fine-scale patterns of vegetation species distributions and structure, as well as the biochemical makeup of vegetation, soil, and surface waters, the availability of these data are limited. Early results from both airborne and satellite systems are promising and hyperspectral remote sensing is certainly an area for future work. Some see the possibility of developing systems capable of remotely fingerprinting biological phenomena, in terms of both taxonomy and condition or health, arising from this technology. Hyperspectral imagery is also very useful for evaluating conditions of coastal marine environments and coral reefs. For example, the CASI (Compact Airborne Spectral Imager) hyperspectral sensor is being used to monitor sea grass spatial distribution (http://www.esa.ssc.nasa.gov/).

There are also a number of commercial satellites that provide relatively fine-scale spatial data of land and water features, including IKONOS (4 meter resolution multi-spectral imagery; 1 meter panchromatic imagery) and QuickBird (2.5 meter resolution multi-spectral imagery; 0.61 meter panchromatic imagery). However, these data are relatively expensive and are typically acquired over relatively small areas (e.g., counties, watersheds) due to narrow sensor swath widths. Nonetheless, they do provide data at the local scales of many ecological studies and can also serve as bridging data sets between such finer scales and broader landscape or regional scales. For example, IKONOS is being used in conjunction with historical aerial photography to determine changes in the extent of coral reefs (Palandro et al. 2003). SPOT satellite data provides various resolutions of spectral and panchromatic imagery (2.5m, 5m, 10m, and 20 m) and has for years been used to the map and monitor numerous Earth features and in associated applications.

Imagery and data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite sensor have been used to characterize geology and soils at relatively high spatial resolutions, especially in drier habitats. Nevertheless, better data for soil characterization are needed for many areas of the Earth, with systems capable of higher-resolution detection of soil types and levels of soil moisture being especially important.

Airborne digital multi-spectral photography provides vital information on vegetation characteristics, stream morphology, coral reef extent, coastline characteristics, and many other Earth and marine features and biophysical variables at relatively high spectral and spatial resolutions. While satellite remote sensing of the Earth's surface has only been in existence for just over 30 years, archives of photographic imagery (while not contiguous at the national level) extend much further back in time (e.g., early 1930s and 1940s). As such, they provide an invaluable time series for understanding landscape changes and associated phenomena. Preservation and digitization of these archives and the unique information they hold is of the utmost importance.

Field and Site Data

There are a number of monitoring programs that collect information on biological, physical, and chemical attributes of ecosystems, some of which are regional and national in scale. Data from these programs have been used to develop, calibrate, apply, and refine ecological models. Examples of national-scale ecological monitoring and assessment programs that produce ecological data on a large number of sites or areas include:

- The Long-term Ecological Research (LTER) network consists of 24 ecologically representative sites across the U.S. that collect data on a wide range of important ecological and biological processes; it is used to develop ecological process models at multiple scales. (NSF sponsored universities and institutes).
- Experimental Watershed Networks operated by the USDA Agricultural Research Service, U.S. Forest Service, and the U.S. Geological Survey, some of which are also LTER sites provide long-term spatially and temporally intensive hydro-climatic measurements and high-resolution watershed characterization with a focus on process-based research.
- Forest Inventory and Analysis (FIA) provides forest health and productivity indicators measured on an annual rotational basis on a range of probabilistic sample sites, mostly on private lands (U.S. Forest Service in collaboration with States).
- Natural Resources Inventory (NRI) supplies a set of ecological and environmental measures taken every five years on probabilistic area samples (but not on Federal Lands; U.S. Natural Resources Conservation Service).
- Breeding Bird Survey offers estimates of breeding bird abundance and diversity on approximately 3,700 25-mile road survey routes (USGS).
- Environmental Monitoring and Assessment Program (EMAP) provides a national survey involving several hundred sites with measurements of physical, chemical, and biological condition of estuaries (in collaboration with NOAA). Also, several hundred survey sites of streams involving chemical, physical habitat, and biological condition measurements. (U.S. EPA in collaboration with the states).
- National Agricultural Statistical Survey (NASS) performs probability based surveys to estimate county and national statistics on pesticide use, crop yield, and other important agricultural statistics (USDA).
- National Wetlands Inventory (NWI) produces national maps of wetland distributions as well as probability-based, area samples of wetland trends. (USFWS).
- The National Estuarine Research Reserve System (NERRS) network of 26 areas representing different biogeographic regions tracks short-term variability and long-term changes in estuarine waters and provides valuable long-term data on water quality and weather at frequent time intervals (NOAA).
- NOAA's Fisheries' Living Marine Resource Surveys provide ship-based surveys of commercial and non-commercial marine organisms.
- NOAA's National Status and Trends Program has been providing data on the status and trends of the coastal environment since 1984.

Integration of Data

Many of the programs listed above have active research and development programs to integrate field data with larger, spatially continuous biophysical data with the aim of making estimates of ecological and biological conditions over broad geographic areas. These involve a wide range of *in situ* data, and empirical and process modeling approaches. Integration of data and models requires an "a priori" consideration of sampling designs and scaling functions, such as the framework developed by the CENR (CENR 1997, Figure 1). Examples of programs that integrate field and spatial data to conduct ecological forecasting include EPA's Regional Vulnerability and Assessment (ReVA) program, the Invasive Species Science Program (USGS, Fort Collins, Colorado, in collaboration with NASA and Colorado State University), the USFS's climate change atlas (Iverson et al. 1999), and several research initiatives in NOAA (see Valette-Silver and Scavia 2003). Extensive research is being conducted at universities and institutes to integrate field and remotely sensed data through development of dynamic, multi-scale process models (see Figure 2). Finally, tools now exist that assist in the development of models. For example, Lifemapper uses the Internet and leading-edge information technology to retrieve records of millions of plants and animals in the world's natural history museums. Lifemapper analyzes these data, computes the ecological profile of each species, maps where the species has been found and predicts where each species could potentially live (www.lifemapper.org). NOAA, the USGS, and the Smithsonian Institute are developing a similar system to map and project risks of invasive species spread into marine, estuarine, and coral reef systems (http://www.nccos.noaa.gov/documents/factsheet_invasivespecies.pdf).

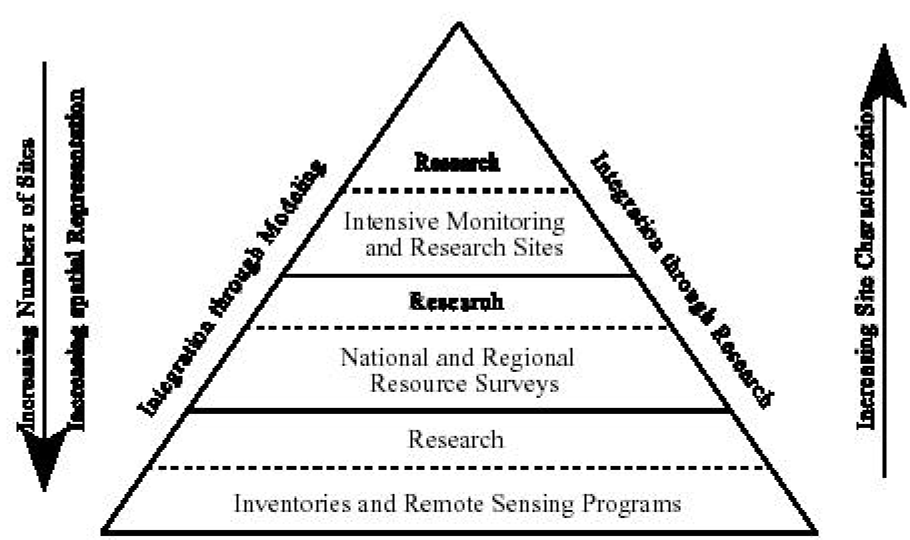

Figure 1 Relationships among different levels of monitoring programs (from CENR 1997)

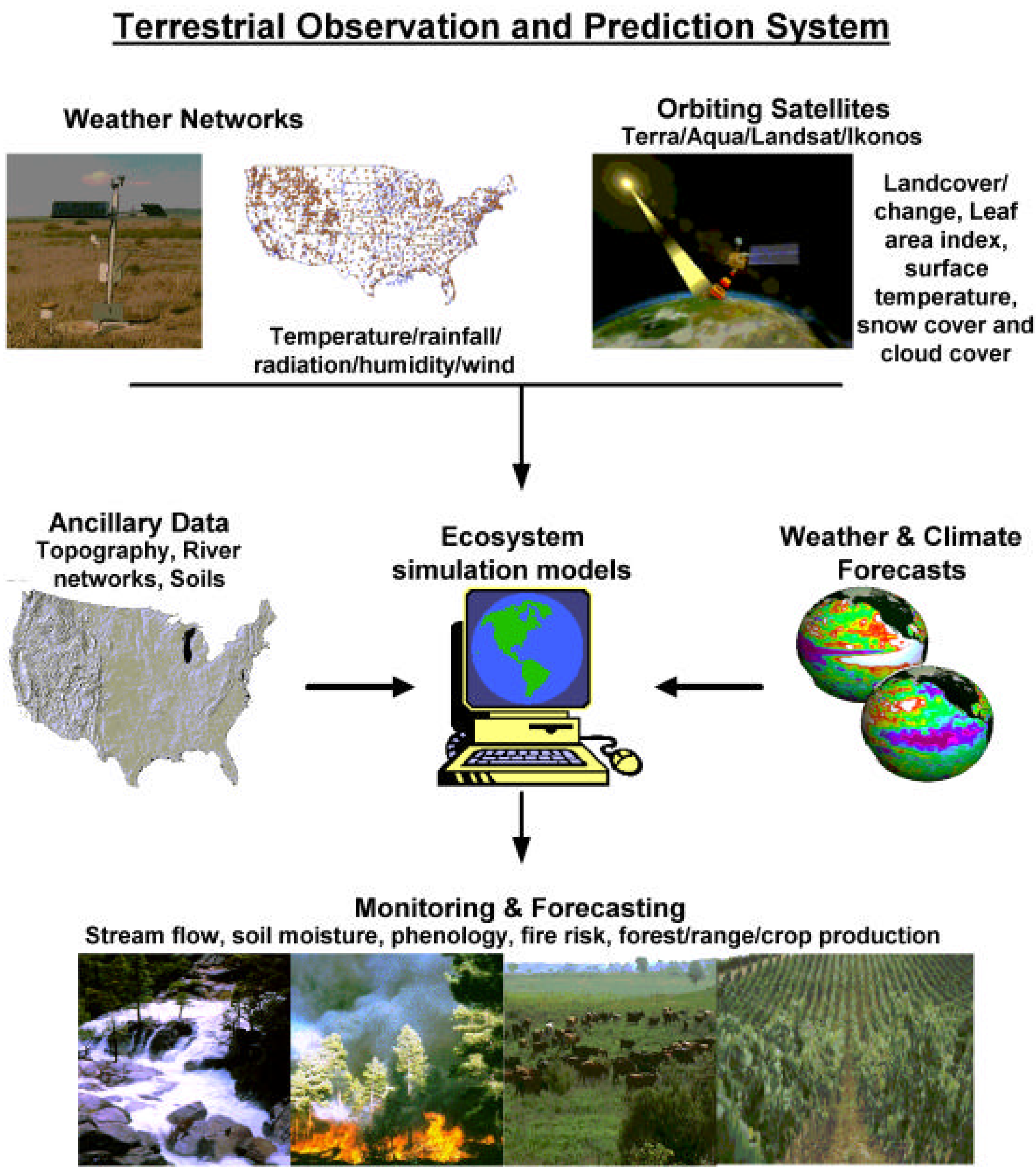

Figure 2 An example of an integrated Earth Observation System framework to address ecological forecasting and risk assessment of land and freshwater ecosystems (Nemani et al. 2003, http://www.ntsg.umt.edu/tops/).

4. Major Gaps and Challenges

Although there are a number of deployed Earth observations systems across the U.S, including individual site monitoring stations and airborne and satellite imagery, lack of interoperability, coordination, and enforcement of Federal Geographic Data Committee (FGDC) data standards within and among these programs prevent optimal use of resulting data and information for ecological forecasting. New approaches in data mining and networking should improve data integration and modeling to a certain extent, but there are a number of issues related to data collection and availability that will limit the success of such programs. Certain types and scales of ecological forecasting are possible given current data and capabilities, as highlighted in sections Table 1 and Table 2, but many gaps still exist. These gaps are summarized in Table 3. There are six general categories of gaps: (1) field and site data (*in situ*), (2) remotely sensed and other spatial data, (3) models, (4) data and system interoperability and data standardization and management, (5) technology transfer, and (6) education gaps. These issues need to be resolved in order to improve and extend our ability to conduct ecological forecasting.

Table 3. Earth observation gaps and needs.

Field and Site Data
Some of the existing field surveys may be biased such that the data are not representative of the ecosystem, area, or ecological and biological processes that they are measuring. This might include biases associated with the proximity of sample sites to roads, or to a certain biophysical setting.
Some of the existing programs may have too few sample sites (sparsely dispersed) to capture spatial variability in ecological processes and conditions. Since many programs use spatial variability to model potential responses of ecological resources to future environmental change (for example, Stohlgren et al. 2003), samples must be representative of a gradient of ecological conditions, and/or stressor conditions.
Some programs do not reveal spatial locations that are necessary to link site conditions to broader landscape conditions, including sites protected by law related to property owner confidentiality. Relatively detailed spatial locations are needed to evaluate quantitative relationships between site measures and broader landscape conditions. In some cases, data on the locations of threatened and endangered species will require special protections.
New technologies are needed for biological and chemical sensors. Wireless networking of embedded sensor devices that can be deployed in remote areas (e.g. measure gas fluxes in soils, from whole ecosystems – AmeriFlux network, and over regions; acoustic sensors for assessing ecosystem health and population dynamics). Additionally, Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV) are needed to measure biological, chemical, and physical variables in marine and coastal environments.
Many taxa and/or important issues related to certain taxa are missed by existing monitoring programs. For example, none of the programs provided information that would have helped forecast the spread of West Nile Virus. Monitoring networks have not been designed to detect species-level changes, and few detect changes in rare and uncommon species. Rare habitats are significantly under-represented in existing monitoring programs.
Outside of the LTER and NOAA National Status and Trends (NS&T) networks, which are relatively limited in its spatial extent and number of sites, there are very few long-term, fixed monitoring sites that can be used to evaluate seasonal and interannual influences, such as climate, on ecological resources and processes. Moreover, there are very few fixed sites

that have a range of chemical, physical, and biological measurements collected over long time periods. Such sites are important in evaluating how biological populations and communities respond to seasonal and interannaul variation in the physical environment. There is a need for a larger network of fixed, long-term ecological monitoring and research sites to address this issue. The National Ecological Observatory Network (NEON, Senkowsky 2003, NRC 2004), sponsored and supported by the National Science Foundation and American Institute of Biological Sciences, is a comprehensive proposal to establish geographically distributed infrastructure across the country, that will broaden the spatial representativeness of ecosystems.
There is a lack of historical data on ecological processes, trends, and disturbances to better inform models as to how ecological and biological resources might change in the future. New advances in molecular phylogenetics are just starting to provide a framework and dataset to evaluate historical relationships between environmental change and processes related to biological diversification and evolution. Yet another rationale for the retention of archival data on land cover and other ecosystem-level conditions is to allow for their use in providing a context for understanding the results of species-level phylogenies.
There is a lack real-time and near-time monitors to evaluate how ecological and hydrological processes respond to varying environmental conditions. For example, we need *in situ* monitors to determine how nitrogen and sediment concentrations vary with flow among catchments in different biophysical settings.
We lack sufficient *in situ* observations of marine ecosystems to monitor changes due to climate variability and other anthropogenic activities such as fishing. In particular, data are lacking on secondary producers and non-exploited fishes that play keystone roles in marine ecosystems.
Remotely Sensed and Other Spatial Data
The spatial resolution of many climate data sets continue to be insufficient to model a set of ecological and hydrological processes occurring at finer spatial scales, especially in the western U.S. where spatial heterogeneity in precipitation is considerably higher than the eastern U.S..
There is a lack affordable remote sensing data that permit estimation of important ecological variables and vegetation classes at spatial scales relevant to many land management decisions.
We lack national databases on soils and geology of sufficient spatial resolution and information content (e.g., soil texture and hydraulic properties) that permit accurate modeling of ecological and physical processes at community and within-watershed scales.
We lack sufficient data on human uses of ecosystems.
There is a lack elevation data of sufficient resolution in coastal areas that permit an accurate assessment of the catchment area of individual water bodies and stream segments, as well as direction of flow. Delineating catchment areas of and flows into water bodies is critical in determining potential point and non-point source pollution contributions to observed ecological conditions.
There is a lack remote sensing technology to estimate the temperature of streams in a spatially and temporally continuous manner. Such estimates are critically important in evaluating fish habitat quality in many streams in the Pacific Northwest

There is a need for technological developments in remote sensing, including: radar and LIDAR satellite systems that will enable the depiction, at suitable spatial resolutions, of the 3rd dimension in structurally complex terrestrial and coastal marine habitats; on-orbit hyperspectral sensors to improve our ability to detect ecological communities (and perhaps species-level differences) and vegetation condition; and measures of soil surface moisture and sea surface salinity.
Modeling
Although many models have been developed that permit ecological modeling and forecasting, there is no central repository or web-based utility that allows a user to access and use these models. However, the EPA has developed a framework and set of standards for models supporting environmental regulation (CREM) and the NBII also is attempting to develop standards for models related to the prediction of species' distributions.
There is no comprehensive approach or standards that have been developed to understand which models will work for a specific range of applications (for example, what model to use to estimate habitat suitability at a regional versus local scale).
Until global climate simulations accurate at the local decision making level are routine there is a need to understand and statistically characterize the influence of large-scale atmospheric forcing (ENSO, PDO, etc) on local climatic variable (precipitation, temperature, etc.).
There is a lack of integration of important biological, chemical, and physical parameters in models.
Many process models are too data and parameter intensive to apply over broader geographic regions (where the questions are regional in scope).
There are a number of ecological processes important to ecological forecasting, that because of scaling complexity and other factors, are difficult to model.
There is a lack of comprehensive methods to estimate and display uncertainty in model estimates, although Smith et al. (2001) and Wickham et al. (2002) have applied logistic regression and Bayesian approaches, respectively, to map the spatial distribution in modeling results.
There is a need for a wide range of *in situ* data for model validation.
There is a need for assessments and testing on appropriate methods to extrapolate point data into wall-to-wall maps.
Data and System Integration, Data Management, Technology Transfer, and Education
There is a lack of a comprehensive information management system that provides one-stop shopping for data, models, standards, tools, and training needed to conduct ecological forecasts.
Computational infrastructure and informatics are needed that provide efficient data querying/mining/analysis/integration of biological, chemical, and physical data for ecological forecasting.
We lack an efficient system for disseminating data and models to those conducting and using ecological forecasts across the country.
There is a lack of comprehensive, web-based programs that would promote training and learning on ecological forecasting at the K-12 and college levels. Web-based programs,

like the EPA's Surf-Your-Watershed (http://www.epa.gov/surf/), have had a dramatic positive impact on the awareness of students about environmental conditions in the watershed in which they reside.
There is a need for new education programs so that the public and the decision makers, as well as researchers, become aware of GIS/map accuracy issues and the subsequent validity of any information they use.

References

Adkins, D.E., K. Droegemeier, S. Feldman, H. Garcia-Molina, M. Klein, D. Messerschmitt, P. Messina, J. Ostriker, and M. Wright. 2003. Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure.

Allen, T.F.H., and T.B. Starr. 1982. Hiearchy: perspectives for ecological complexity. Chicago: Chicago University Press.

Andelman, S.C., C. Bowles, M. Willig, and R. Waide. 2004. Understanding environmental complexity through a distributed knowledge network. BioScience 54(3):240-246.

Aycrigg, J.L., S.J. Harper, and J.D. Westervelt. 2004. Simulating land use alternatives and their impacts on a desert tortoise population in the Mojave Desert, California. Pp. 249-273, in Costanza, R., and A. Voinov, eds., Landscape simulation modeling. Springer-Verlag, New York.

Baker, J. P., D.W. Hulse, S.V. Gregory, D. White, J. Van Sickle, P.A. Berger, D. Dole, and N.H. Schumaker. 2004. Alternative futures for the Willamette River Basin, Oregon. Ecological Applications 14:313-324.

Berger, P.A., and J. P. Bolte. 2004. Evaluating the impact of policy options on agricultural landscapes: an alternative-futures approach. Ecological Applications 14:342-354.

Bradley, M.P, and E.R. Smith. 2004. Using science to assess environmental vulnerabilities. Environmental Monitoring and Assessment 94:1-7.

CENR (Committee on Environment and Natural Resources). 1997. Integrating the Nation's environmental monitoring and research networks and program: a proposed framework. Subcommittee on Ecological Systems, Washington, D.C., 82 pp.

CENR (Committee on Environment and Natural Resources). 2001. Ecological forecasting: agenda for the future. Subcommittee on Ecological Systems, Washington, D.C., 12 pp.

Claggett, P.R., C.A. Jantz, S.J. Goetz, and C. Bisland. 2004. Assessing development pressure in the Chesapeake Bay Watershed: an evaluation of two land-use change models. Environmental Monitoring and Assessment 94:129-146.

Clark, J. S., S. R. Carpenter, M. Barber, S. Collins, A. Dobson, J. A. Foley, D. M. Lodge, M. Pascual, R. Pielke, Jr., W. Pizer, C. Pringle, W. V. Reid, K. A. Rose, O. Sala, W. H. Schlesinger, D. H. Wall, and D. Wear. 2001. Ecological forecasts: an emerging imperative. Science 293(5530):657-660

Costanza, R., and A. Voinov. 2004. Introduction: spatially explicit landscape simulation models. Pp. 3-20, in Costanza, R., and A. Voinov, eds., Landscape simulation modeling. Springer-Verlag, New York.

Davis, G.E. 2004. National park stewardship and 'Vital Signs' monitoring: A case study from Channel Islands National Park, California., Aquatic Conservation, in press.

Deal, B., C. Farello, M. Lancaster, T. Kompare, and B. Hannon. 2004. A dynamic model of the spatial spread of infectious disease: the case of fox rabies in Illinois. Pp. 275-300, in Costanza, R., and A. Voinov, eds., Landscape simulation modeling. Springer-Verlag, New York.

De Beurs, K.M., and G.M. Henebry. 2004. Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan. Remote Sensing and the Environment 89:497-509.

ESA (Ecological Society of America). 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. Issues in Ecology 2:1-16.

Fonseca, M.S., P.E. Whitfield, N.M. Kelly, and S.S. Bell. 2002. Modeling seagrass landscape pattern and associated ecological attributes. Ecological Applications 12:218-237.

Fritz, C., F. Sklar, T. Waring, A. Voinov, R. Costanza, and T. Maxwell. 2004. Development and application of the Everglades landscape model. Pp. 143-171, in Costanza, R., and A. Voinov, eds., Landscape simulation modeling. Springer-Verlag, New York.

Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page. 2003. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Pp. 19-22, in Valette-Silver, N.J., and D. Scavia, eds., Ecological forecasting: new tools for coastal and ecosystem management. NOAA Technical Memorandum NOS NCCOS 1. 116 pp.

Goward, S.N., J.R.G. Townshend, V. Zanoni, F. Policelli, T. Stanley, R. Ryan, K. Holekamp, L. Underwood, M. Pagnutti, and R. Fletcher. 2003. Acquisition of Earth science remote sensing observations from commercial sources: lessons learned from the Space Imaging IKONOS example. Remote Sensing of the Environment 88:209-219.

Hall, M.H.P., and D.B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850 -2100.

Herrmann, S.M., and C.F. Hutchinson. 2004. The changing contexts of the desertification debate. Environmental Monitoring and Assessment, in press.

Hulse, D.W., A. Branscomb, and S.G. Payne. 2004. Envisioning alternatives: using citizen guidance to map future land and water use. Ecological Applications 14:325-341.

Hutchinson, C.F. 2001. Famine and Famine Early Warning: Some Contributions by geographers. Yearbook of the Association of Pacific Coast Geographers. 63:137-144

IGBP-IHDP. 1999. Land-use and land-cover change implementation strategy. Stockholm, International Geosphere-Biosphere Programme and International Human Dimensions Programme.
Iverson, L.R. in press. Adequate data of known accuracy are critical to advancing the field of landscape ecology . In Wu, J., and R. Hobbs (eds.), Key Topics and Perspectives in Landscape Ecology. Cambridge University Press.

Iverson L.R., M.E. Dale, C.T. Scott, and A.M. Prasad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity in Ohio forests. Landscape Ecology 12:331-348.

Iverson L.R., A.M. Prasad. 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecological Monographs 68:465-485.

Iverson L.R., A.M. Prasad, B.J. Hale, and E.K. Sutherland. 1999. An atlas of current and potential future distributions of common trees of the eastern United States. General Technical Report NE-265. Northeastern Research Station, USDA Forest Service. 245 pp.

Jackson, L.E., S.L. Bird, R.W. Matheny, R.V. O'Neill, D. White, K.C. Boesch, and J.L. Koviach. 2004. A regional approach to projecting land-use change and resulting ecological vulnerabilities. Environmental Monitoring and Assessment 94:231-248.

Jones, K.B., A.C. Neale, M.S. Nash, R.D. Van Remotel, J.D. Wickham, K.H. Riitters, and R.V. O'Neill. 2001a. Predicting nutrient and sediment loadings to streams from landscape metrics: a multiple watershed study from the United States Mid-Atlantic Region. Landscape Ecology 16:301-312.

Kastens, J.H., K.P. Price, D.L. Kastens and E.A. Martinko. 2001. Forecasting Pre-harvest Crop Yields using Time Series Analysis of AVHRR NDVI Composite Imagery. Proceedings, Annual Convention, American Society of Photogrammetric Engineering and Remote Sensing. St. Louis, Missouri, April 23 - 27.

Kepner, W.G., D.J. Semmens, S.D. Bassett, D.A. Mouat, and D.C. Goodrich. 2004. Scenario analysis for the San Pedro River, analyzing hydrological consequences of a future environment. Environmental Monitoring and Assessment 94:115-127.

Kerr, J.T., and M. Ostrovsky. 2003. From space to species: ecological applications for remote sensing. Trends in Ecology and Evolution 18:299-305.

Kratz, T.K., L.A. Deegan, M.E. Harmon, and W.K. Lauenroth. 2003. Ecological variability in space and time: insights gained from the U.S. LTER program. BioScience 53:57-67.

Lambin, E.F. 1994. Modeling deforestation processes: a review. Luxemburg, European

Commission.

Lee, R.G., R. Flamm, M.G. Turner, C. Bledsoe, P. Chandler, C. DeFerrari, R. Gottfried, R.J. Naiman, N. Schumaker, and D. Wear. 1992. Integrating sustainable development and environmental vitality: a landscape ecology approach. Pp. 499-521, in Naiman, R.J., ed., Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

Li, H., and J.F. Reynolds. 1997. Modeling effects of spatial pattern, drought, and grazing on rates of rangeland degradation: a combined Markov and cellular automaton approach. Pp. 211-230, in D.A. Quattrochi, D.A., and M.F. Goodchild, eds., Scale in remote sensing and GIS. Lewis Publishers, New York.

Longcore, T., and C. Rich. 2004. Ecological light pollution. Frontiers in Ecology and the Environment 2:191-198.

Loucks, O.L., and R.F. Gorman. 2004. Regional ecosystem services and the ratin of investment opportunities. Frontiers in Ecology and the Environment 4:207-216.

Martin, J.F. 2003. Simulating coastal environments with landscape models: applications in the Mississippi Delta and Lake Erie. Pp. 29-35, in Valette-Silver, N.J., and D. Scavia, eds., Ecological forecasting: new tools for coastal and ecosystem management. NOAA Technical Memorandum NOS NCCOS 1. 116 pp.

Matheny, R.W., and K. Endres. 2003. Land-use change due to urbanization for the middle Atlantic integrated assessment region of the eastern United States. Pp. 777-786, in Rapport, D.J., W.L Lasley, D.E. Rolston, N.O. Nielsen, C.O. Qualset, and A.B. Damania, eds., Managing for healthy ecosystems. Lewis Press, New York.

McCade, G.J, M.A. Palecki, and J.L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences 101:4136-4141.

Monaco, M.E., and R.J. Livingston. 2003. Forecasting oyster mortality in relation to variations in freshwater inflow into the Apalachicola-Chattahoochee-Flint (AFC) Basin. Pp. 67-71, in Valette-Silver, N.J., and D. Scavia, eds., Ecological forecasting: new tools for coastal and ecosystem management. NOAA Technical Memorandum NOS NCCOS 1. 116 pp.

Meyerson, L.A., and J.K. Reaser. 2003. Bioinvasions, bioterrorism, and biosecurity. Frontiers in Ecology and the Environment 1:298-306.

Nemani, R.R., M.A. White, Lars Pierce, Petr Votava, Joseph Coughlan and S.W. Running. 2003. Biospheric monitoring and ecological forecasting, Earth Observation Magazine, 12 (2): 6-8.

National Research Council. 2004. NEON addressing the nation's environmental challenges. National Academies Press, Washington, DC.

NASA 2004. NASA Earth science enterprise: Earth science for ecological forecasting.

Neale, A.C., Jones, K.B., Nash, M.S., Van Remortel, R.D., Wickham, J.D., Riitters, K.H., and R.V. O'Neill. 2003. Pp. 577-588, in Rapport, D.J., W.L Lasley, D.E. Rolston, N.O. Nielsen, C.O. Qualset, and A.B. Damania, eds., Managing for healthy ecosystems. Lewis Press, New York.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A hierarchical concept of ecosystems. Princeton: Princeton University Press.

Parks, B.O, M.D. Fornwall, and J.F. Quinn. 2003. First NBII biodiversity modeling workshop: results and recommendations. Proceedings of the NBII Biodiversity Modeling Workshop, Maui, HI. 36pp.

Palandro, D., S. Andrefouet, P. Dustan, and F.E. Muller-Karger. 2003. Change detection in coral reefs using Ikonos satellite imagery and historical aerial photographs. International Journal of Remote Sensing 24:873-878.

Peterson, A. T., D. A. Vieglais, and J. K. Andresean. 2003. Migratory birds modeled as crtical transport agents for West Nile Virus in North America. Vector-Borne and Zoonotic Diseases, 3 (1): 27-37.

Pielke, Jr., R. A. and R. T. Conant. 2003. Best practices in prediction for decision making: lessons from the atmospheric and Earth sciences, Ecology, 84:1351-1358.

Rastetter, E.B., J.D. Aber, D.P.C. Peters, D.S. Ojima, and I.C. Burke. 2003. Using mechanistic models to scale ecological processes across space and time. BioScience 53:68-76.

Reid, W., N. Ash, E. Bennett, P. Kumar, M. Lee, N. Lucas, H. Simons, V. Thompson, and M. Zurek. 2002. Millennium ecosystem assessment methods http://www.millenniumassessment.org/en/products.aspx)

Reynolds, C.A., M. Yitayew, D.C. Slack, C.F. Hutchinson, A. Huete, M.S. Petersen. 2000. Estimating crop yields and production by integrating the FAO Crop Specific Water Balance model with real-time satellite data and ground-based ancillary data. International Journal of Remote Sensing 21(18): 3487-3508.

Rollins, M.G., R.E. Keane, and R.A. Parsons. 2004. Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling. Ecological Applications 14:75-95
Running, S.W., R.R. Nemani, F.A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto. 2004. A continuous satellite-derived measure of global terrestrial primary production. BioScience 54:547-560.

Scavia, D., J.D. Field, and D. F. Boesch. 2003. Forecasting climate impacts on coastal ecosystems. Pp. 23-28, in Valette-Silver, N.J., and D. Scavia, eds., Ecological forecasting: new tools for coastal and ecosystem management. NOAA Technical Memorandum NOS NCCOS 1. 116 pp.

Senkowsky, S. 2003. NEON: planning for a new frontier in biology. BioScience 53:456-461.

Smith, J.H., Wickham, J.D., Norton, D., Wade, T.G., and Jones, K.B. 2001. Utilization of landscape indicators to model potential pathogen impaired waters. Journal of American Water Resources Association. 37:805-814.

Stohlgren, T.J., D.T. Barnett, and J.T. Kartesz. 2003. The rich get richer: patterns of plant invasions in the United States

Thomas, C.D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A.S. van Jaarsveld, G.F. Midgley, L. Miles, M.A. Ortega-Huerta, A.T. Peterson, O.L. Phillips, and S.E. Williams. 2004. Extinction risk from climate change. Nature 427:145-148.

Tucker, C.J., D.M. Grant, and J.D. Dykstra. 2004. NASA's global orthorectified Landsat data set. Photogrammetric Engineering & Remote Sensing 70:313-322.

Turner, W., S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology and Evolution 18:306-314.

Valette-Silver, N.J., and D. Scavia. 2003. Introduction to ecological forecasting: new tools for coastal and marine ecosystems management. Pp. 1-4, in Valette-Silver, N.J., and D. Scavia, eds., Ecological forecasting: new tools for coastal and ecosystem management. NOAA Technical Memorandum NOS NCCOS 1. 116 pp.

Van Rompaey, A.J.J., and G. Govers. 2002. Data quality and model complexity for regional scale soil loss. International Journal of Geographical Information Science 16:663-680.

Voinov, A., R. Costanza, R.M.J. Boumans, T. Maxwell, and H. Voinov. 2004. Patuxent landscape model: integrated modeling of a watershed. Pp. 197-232, in Costanza, R., and A. Voinov, eds., Landscape simulation modeling. Springer-Verlag, New York.

White, D., P.G. Minotti, M.J. Barczak, J.C. Sifneos, K.E. Freemark, M.V. Santelmann, C.F. Steinitz, A.R. Kiester, and E.M. Preston. 1997. Assessing risks to biodiversity from future landscape change. Conservation Biology 11:349-360.

Whitley, D. 2001. An overview of evolutionary algorithms: practical issues and common pitfalls. Information and Software Technology 43:817-831.

Wickham, J.D., R.V. O'Neill, K.H. Riitters, E.R. Smith, T.G. Wade, K. B. Jones. 2002. Geographic targeting of increases in nutrient export due to future urbanization. Ecological Applications, 12(1):93-106.

Woolhiser, D.A., T.O. Keefer, and K.T. Redmond. 1993. Southern oscillation effects on daily precipitation in the southwestern United States. Water Resources Research 29:1287-1295.

Zhang, X., and Y. Wang. 2002. Spatial dynamic modeling for urban development. Photogrammetric Engineering and Remote Sensing 67:1049-1057.

http://www.fs.fed.us/ne/delaware/atlas

http:/www.fs.fed.us/ne/delaware/4153/global/littlefia/index.html

http://www.unomaha.edu/~jmccarty/Papers/EcologicalForecasting.pdf

http://www.nbii.gov/about/pubs/efbrochure/index.html

http://www.oceanservice.noaa.gov/topics/coasts/ecoforecasting/welcome.html

http://www.ocean.us

http://www.earth.nasa.gov/eseapps/theme13.htm

http://www.unep.org/geo2000/ov-e/index.htm

http://www.issues.org/issues/16.3/reid.htm

http://www.epa.gov/nerlesd1/land-sci/ReVA/index.html

http://www.millenniumassessment.org/en/index.aspx

http://www.i4sd.org/TCDDM/Stein1.htm

http://www.gwsp.org/

http://www.igbp.kva.se/

http://www.pik-potsdam.de/~bahc/

http://www.unesco.org/water/

http://www.unesco.org/water/wwap/index.shtml

http://www.fia.fs.fed.us/

http://www.nrcs.usda.gov/technical/NRI/

http://www.mbr-pwrc.usgs.gov/bbs/bbs.html

http://www.audubon.org/bird/cbc/

http://www.usda.gov/nass/

http://www.nwi.fws.gov/

http://www.lternet.edu/index.html

http://www.waterwatch.org.au/

www.lifemapper.org

http://invasivespecies.gsfc.nasa.gov/

http://servir.nsstc.nasa.gov/home.html

http://www.epa.gov/surf/

http://www.landfire.gov/

http://lternet.edu/

http://ccmaserver.nos.noaa.gov/rsd/products.html

http://www.esa.ssc.nasa.gov/

http://www.nccos.noaa.gov/documents/factsheet_invasivespecies.pdf

http://www.csc.noaa.gov/crs/habf/bulletin.html

http://frogweb.nbii.gov/narcam/

http://www.ntsg.umt.edu/tops/

http://www.wcc.nrcs.usda.gov/climate/gem.html

http://www.cuahsi.org