# Activity Report

# 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, ecosystem services and/or natural capital are derived from specific scenarios of future human resource use, climate change, and policy actions. 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 other goals described in this report, 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 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 environmental disasters and to promote sustainable development. In this regard, forecasting plays an important role in early warning. Analogues 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 ENSO events.

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). These approaches often use 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.

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. Rather, the second general approach uses 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 to identify a range of alternative environmental futures (White et al. 1997, Baker et al. 2004, Hulse et al. 2004, Kepner et al. 2004). 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. Use of empirical models is a common approach 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.

## 2. User Requirements

Ecological forecasting requires the acquisition of a wide range of environmental data, as well 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 assessment questions. 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 texture and land cover composition and patterns, which result in different sediment and run-off projects 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).

The following are the examples of the types of questions that might be asked in association with ecological forecasting:

**Consequences and Vulnerability**

Under different scenarios of global climate change, what is the spatial distribution of terrestrial ecosystems that will experience greater intensity and frequency of catastrophic fires? What is the likelihood that these ecosystems will transition into a less desirable state? Which areas will also exhibit the greatest likelihood of loss of property and human lives?

Under different scenarios of global climate change, which river basins and streams have the highest probability of greater than 50% loss in aquatic and riparian biological diversity?

Under different climate change scenarios, which forests are likely to experience greater than a 25% decline in productivity? What will be the impact on the forest products economy? What are the spatial relationships between declines in forest productivity and species diversity?

Under different climate change or land use scenarios, what areas are most vulnerable to increases of invasive species?

Under different climate change, land use, or clean air policy scenarios, how will the spatial pattern in deposition of nitrogen, sulfur, and mercury change? What will be the potential impact on terrestrial and aquatic ecosystems? Will fish become more or less safe to eat as a result of these changes?

Under different climate change, land use, and urbanization scenarios, which productive agricultural lands will be at greatest risk of being lost?

What are the impacts of ENSO or other seasonal to interannual climate events on the productivity of selected coastal or pelagic fisheries?

**Planning and Management**

How will green technologies offset ecological and hydrologic changes associated with urbanization, desertification, and/or climate change?

What observation tools and models will decision makers and the general public need to understand and address changes to terrestrial and aquatic ecosystems

What Best Management Practices (BMPs) can be employed 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 conversation 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?

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?

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?

There are and will continue to be a number of organizations and agencies that will need earth observation data and models to forecast changes in important ecological resources and processes given a range of scenarios of potential future environmental conditions. These will include county, city, and watershed organizations trying to evaluate options for smart growth (Voinov et al. 2004, Berger and Bolte 2004), as well as larger geographic initiatives to evaluate vulnerability of ecological resources and processes to future 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.

Because of the diverse needs for forecasting at a range of scales, there will be a comprehensive and wide range of earth observations needs. However, these observations are likely to fall out into two general classes: spatially continuous biophysical data, 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 (see 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 data also can be used to construct ecosystem classification approaches to reduce variability in the response of ecosystems to perturbations, and hence improve predictability and forecasting.

The following is an initial list of earth observations required to conduct ecological forecasting.

- 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.
- 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)

- Digital elevation model data (10 meters 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, levey)
  (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)
- 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)
- 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
- 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, 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)
- Data on the magnitude and distribution of major disturbances (e.g., fires) 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 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, and physical data described above
  (to improve models and ecological forecasting at community and local scales)

## 3. Deployed Observing Capabilities and Commonalities

### Remotely-Sensed Spatial Data

A number of geospatial data sets are currently available that are used for observations, monitoring, and ecological modeling of 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 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 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 nationally is 2006.

The AVHRR and 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 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 biomass burning, 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 a cloud product 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 signals in patterns of greenness, which can then be used to help in the identification of plant species composition. Additionally, MODIS provides a set of vegetation bands at 250 meter and 500 meter resolutions, providing higher resolution imagery for several of the land products useful in ecological modeling.

There has been considerable use of data from satellite radars (e.g., RADARSAT and JERS-1) and airborne radar systems to assess surface roughness, 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 read 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. 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 under a vegetation canopy and have proved useful at mapping wetlands, whether permanently or seasonally inundated.

Laser systems, known as lidars, are 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 (for example, within floodplains to evaluate surface flow and in coastal regions where finer-scale digital elevation data is needed). However, to date, vegetation LIDAR sensors have generally flown on airplanes, making the data relatively expensive to acquire. In a marine context, lidars provide high-resolution bathymetry data in coastal zones.

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.

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 small areas 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.

Airborne imagery and data from the ASTER satellite sensor have been used to characterize geology and soils at relatively high resolutions, especially in drier habitats. Nevertheless, better data for soil characterization are needed for many areas of this planet, with systems capable of higher-resolution detection of soil types and levels of soil moisture being especially important.

Digital multi-spectral photography is available from aircraft and provides vital information on vegetation characteristics, stream morphology, and other biophysical variables at fine spatial scales. While satellite remote sensing of the Earth's surface has only been in existence for just over 30 years, archives of photographic imagery extend much further back in time. As such, they provide an invaluable time series for understanding landscape changes and associated phenomena. Preservation of these archives and the unique data sets 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, and apply ecological models. Examples of national-scale ecological monitoring and assessment programs that produce ecological data on a large number of sites or areas include:

- Long-term Ecological Research (LTER) network … 24 ecologically representative sites across the US that collect data on a wide range of important ecological and biological processes that are used to develop ecological process models at multiple scales. (NSF sponsored universities and institutes)
- Forest Inventory and Analysis (FIA) … forest health and productivity indicators measured on a annual rotational basis on a range of probabilistic sample sites, mostly on private lands (US Forest Service in collaboration with States)
- Natural Resources Inventory (NRI) … a set of ecological and environmental measures taken every five years on probabilistic area samples (but not on Federal Lands (US Natural Resources Conservation Service))
- Breeding Bird Survey … estimates of breeding bird abundance and diversity on approximately 3700 25-mile road survey routes (USGS)
- Christmas Bird Count … bird counts and species abundance on two thousand sites around the US taken by approximately 50,000 volunteers. (The Audubon Society)
- Environmental Monitoring and Assessment Program (EMAP) … 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. (US EPA in collaboration with the states)

- National Agricultural Statistical Survey (NASS) … agency in USDA that conducts probability based surveys to estimate county and national statistics on pesticide use, crop yield, and other important agricultural statistics.
- National Wetlands Inventory (NWI) … produces national maps of wetland distributions as well as probability-based, area samples of wetland trends. (US Fish and Wildlife Service).
- 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… provides valuable long-term data on water quality and weather at frequent time intervals (NOAA).

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 empirical and process modeling approaches which are used in ecological forecasting. Other 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), 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 discussion in sections 4.6.1 and 4.6.2). Finally, tools have been developed that assist in developing 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 the 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).

## 4. Gap Analysis and Associated Needs

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 cohesion and coordination among these programs prevent optimal use 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 1. and 2., but the following gaps and issues need to be resolved in order to improve and extend our ability to conduct ecological forecasting.

### 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. 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.
- Outside of the LTER network, which is 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.
- We lack 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.
- We 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.
- 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)

**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 US where spatial heterogeneity in precipitation is considerable higher than the eastern US
- We lack affordable remote sensing data that permit estimation of important ecological variables 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) that permit accurate modeling of ecological and physical processes at community and within-watershed scales

- We 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.
- We 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
- We need 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).
- 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)
- 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, cannot be modeled.
- We lack 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.

**Data Management, Technology Transfer, and Education**

- We lack a comprehensive information management system that provides one-stop shopping for data, models, standards, and training needed to conduct ecological forecasts.
- Computational infrastructure and informatics are needed that provides efficient data querying/mining/analysis of biogeophysical data for ecological forecasting.
- We lack an efficient system for disseminating data and models to those conducting ecological forecasts across the country
- We lack a comprehensive, web-based program 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, have had a dramatic positive impact on the awareness of students about environmental conditions in the watershed in which they reside.

**5. Partnerships Interagency/International/Commercial**

In the United States, this forecasting capability will require integrating more than 30 major U.S. remote sensing programs, environmental monitoring networks, natural resource and agricultural systems surveys, and site-based research programs. The rapidly developing National Biological Information Infrastructure (NBII), GAP Analysis Program, the National Map Program, NASA's Earth Science Enterprise, landscape-based, comparative risk programs, such as EPA's Regional Vulnerability Assessment (ReVA), and the Long Term Ecological Research (LTER) network can help provide necessary information architecture, tools, and web-based data and assessment applications to access and integrate biodiversity and ecosystem information across multiple scales.

Regional and global earth observing systems and networks include Global GRID, the Global Ocean Observing System (GOOS), Global Terrestrial Observing System (GTOS), Ecological Monitoring and Assessment Network (EMAN,Canada). International initiatives that are involved in ecological forecasting include the Millennium Assessment, International Geosphere Biosphere Program (IGPB), the Integrated Ocean Observing System (IOOS), the Intergovernmental Panel on Climate Change (IPCC), the Global International Waters Assessment, Global Biodiversity Information Facility (GBIF), and the UNEP Global Environmental Outlook.

One example of a successful and extremely relevant partnership can be found in the Multi-Resolution Land Characteristics (MRLC) consortium that was formed in 1992 between several Federal agencies in order to share the cost of acquiring satellite-based remotely sensed data for their environmental monitoring programs.

The MRLC consortium included the U.S. Geological Survey (USGS), the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Forest Service (USFS), the National Atmospheric and Space Administration (NASA) and the Bureau of Land Management (BLM).

The MRLC utilized the combined common user requirements with the efficiency of combined federal agency purchase to acquire a national dataset of Landsat Imagery and to develop several LULC datasets.

From the 1990s through the present, the MRLC resulted in several successful national mapping programs, including the: (1) Coastal Change Analysis Project (C-CAP) administered by NOAA; (2) Gap Analysis Project (GAP) directed by the Biological Resources Division of the USGS; and the National Land Cover Data (NLCD) project directed by both the USGS and EPA.


Figure X. The Multi- Resolution Land Characteristics (MRLC) Consortium is an outstanding example of a Federal Agency partnership to acquire and develop remote sensing data and products.

## 6. Capacity Building

The following six thematic areas should be considered for capacity building:

1. **Convert and Integrate Existing Biological and Ecological Data to Digital and Accessible Formats**
   Ecological forecasts cannot be produced without reliable information about the current and historical condition of ecosystems. Likewise, the success of decisions made in response to specific forecasts cannot be evaluated without ongoing monitoring of change. Rapid advances in remote sensing and *in situ* sensing ("in the actual place"; contrasted with "remote") offer new opportunities to provide these data. However, new observation, modeling, and data management tools are needed to deal with gathering, integrating, and interpreting complex biological and chemical data, and making them available. There is a large gap (and need) in monitoring data for biota and how biota responds to environmental changes over time.

2. **Understand Ecosystem Composition, Structure, and Functioning**
   A new agenda is needed to respond to relevant recommendations in recent reports of the National Academy of Sciences, the President's Committee of Advisors on Science and Technology (PCAST), and the National Science Board. These include studies to improve understanding of the role of biological diversity in determining ecosystem resilience and in quantifying ecological scale interactions. We need to improve ways of modeling movement of nutrients, carbon, water, and other substances through biota, soil, sediment, water, and air, and of estimating how ecosystems respond to combinations of stresses at local and regional scales.

3. **Monitor Ecosystem Status and Trends, and Make Complex Data Available**
   A central challenge for ecological forecasting is to develop decision support tools for translating the rapidly increasing ecological knowledge base into information needed by decision makers and conversely, the ability to translate human decision making into ecological functions. The combination of complex interactions among a large number of components with the variable nature

of ecosystems and their driving forces, makes the development of such tools a significant challenge.

The ability to create ecological knowledge from environmental sensors, monitoring, experiments, and legacy data requires adopting an end-to-end life-cycle approach to all aspects of data and its management. The necessity for information management (ready access, metadata, standards, security, archival, and retrieval) and cyber infrastructure investments (high-performance computing, visualization, technology trends, digital libraries, databases, distributed systems, middleware, and collaboration technology) are only now being realized as critical to enabling scientific discovery, knowledge, and developing effective ecological forecasts (Adkins et al. 2003). Additionally, monitoring programs should be expanded through volunteers. In the US, volunteers are critical to collection of bird species data (Breeding Bird Survey and the Christmas Bird Count). In Australia, biological and chemical samples of streams are collected by a network of volunteers through the Water Watch program. Volunteer programs not only expand important data collection activities but they also dramatically increase awareness and education of the public about critical environmental issues.

4. **Develop and Improve Ecological Prediction and Interpretation Tools**
All forecasting approaches require the development of models to evaluate how ecological goods and services will change under different change scenarios. Therefore, this is a very important area of research (IGBP-IHDP 1999). There are a number of modeling approaches used, all with varying assumptions, limitations, and potential benefits. These include but are not limited to statistical (models based on empirical studies… Jones et al. 2001), equation (static models based on known functions, Lambin 1994), system (models based on ecological, biological, and hydrological processes, Zhang and Wang 2002), expert (use of Bayesian and expert system models to use qualitative data, Lee et al. 1992), cellular (grid-based models, Li and Reynolds 1997), and evolutionary models (models that evolve during analytical processing to consider complex relationships, Whitley 2001).

5. **Increase the Number of Researchers and Applications Specialists in Ecological Forecasting**
Developing effective ecological forecasting will require collaboration, networking, and partnerships with a broad constituency of application specialists. To develop the capacity to derive specific scenarios of future human resource use, climate change, and policy actions will require the formation of "collaboratories" among ecologists, economists, social scientists, climatologists, natural resource and agricultural specialists, and policy and decision makers. Such undertakings pose new challenges in coordination, communication, and synthesis of heterogeneous data into knowledge (Andleman et. al. 2004). Training programs like NSF's Integrative Graduate Education and Research Traineeships (IGERT) is catalyzing just such a cultural change in graduate education by establishing innovative new models for graduate education and training in a fertile environment for collaborative research that transcends traditional disciplinary boundaries.

6. **Develop and Test a Comprehensive Forecasting Framework through Pilot and Case Studies**
A comprehensive and web-based framework should be developed to pull together

data and models to conduct a range of ecological forecasts. Additionally, this framework should include aspects of volunteer and educational components. The framework should be tested through geographically targeted pilot studies involving a number of partnership agencies and organizations.

**7. Future Earth Observation Systems – One Example**

The NSF's proposed National Ecological Observatory Network (NEON) is an example of potentially soon to be implemented systems. NEON will provide the capacity for nationally networked research, communication, and informatics infrastructure for collaborative, comprehensive and interdisciplinary measurements and experiments on ecological systems. NEON will allow multi-disciplinary teams across the US to conduct simultaneous studies on the fundamental biological processes underlying climate change, the spread of invasive species, the ecology of emerging diseases, biogeochemical cycles, or biodiversity (NRC 2004). Deployed sensor networks connected to data portals and repositories will permit rapid and widespread sensing of the environment. NEON's synthesis, computation, and visualization infrastructure will create a virtual laboratory that will permit the development of ecological forecasting and a predictive understanding of the direct effects and feedbacks between environmental change and biological processes.

Additional time is needed to evaluate future earth observation systems.

**8. Summary**

The following are suggested as initial steps to improve ecological forecasting

- Continuity of Landsat-type satellite remote sensing data to provide critical information on land cover and other land surface features and develop the new technologies (outlined in this subchapter) necessary to capture other important environmental parameters either remotely or *in situ*
- National digital databases on soils (SURRGO) and geology at a scale of 1:100,000
- Establishment of long-term biological and ecological monitoring sites through cooperation with existing monitoring programs and proposed monitoring programs like NEON.
- Awareness of and access to data and models via technology insights
- Comprehensive framework for ecological forecasting and test its concept through geographically targeted pilots involving a number of partners and educational institutes
- Organizational mechanisms and technologies, and promote a working environment that will sustain critical long-term observations and data collections
- Outreach and educational approach to foster volunteer and student involvement in data collection … such an approach will dramatically improve public awareness and concern for key future environmental issues
- Web-based site that will promote the development and use of data, models, and standards for ecological forecasting

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