CHAPTER 13

Importance of Land Cover and Biophysical Data in Landscape-Based Environmental Assessments

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ABSTRACT

Land cover and other digital biophysical data play important roles in environmental assessments relative to a large number of environmental themes and issues. These data have become especially important given the pace and extent of land cover change across the globe and world-wide concern for issues such as global climate change. However, land cover and digital biophysical data by themselves are not sufficient for broad-scale environmental assessments. These data must be combined with in situ data collected from comprehensive research and monitoring programs to derive and interpret broad-scale environmental condition. I summarize important uses of land cover and other biophysical data in environmental assessments and emphasize the importance of spatially explicit integration of these data to address critical environmental issues. I also discuss the importance of comprehensive, regional and national in-situ data in the development of landscape indicators and models and the need to maintain and develop new in-situ monitoring programs.

Key words: *Land cover, environmental assessments, landscape indicators, biophysical data, multi-scale analysis*

INTRODUCTION

Spatially continuous digital databases on land cover and other important biophysical attributes (soils, elevation, topography, etc.) have become increasingly available via websites and data portals. Coupled with advances in computer technology, including processing speed, data capacity, software development (e.g., geographic information systems and statistical programs), and distributed network capabilities, this availability now makes it possible to conduct environmental assessments at multiple scales over relatively large geographic areas (Wascher 2005, Jones et al. 2008). This is especially

true of land cover data, which are now available for the entire conterminous United States at a 30 m resolution for two time periods (early 1990s and early 2000s, Homer et al. 2004). This provides for an unprecedented evaluation of land cover change and the consequences of change on a wide range of ecological goods and services. Here I highlight several examples of the use of land cover and other wall-to-wall biophysical data in environmental assessments, including those related to environmental status and trends, impact analysis, vulnerability and risk assessments, ecological forecasting, and alternative future landscape analyses. I also emphasize the importance of combining land cover with other wall-to-wall biophysical data to enhance environmental assessments. I conclude with a discussion of key components of landscape assessments.

LANDSCAPE-BASED ENVIRONMENTAL ASSESSMENTS

Landscape-based environmental assessments generally fall into one or a combination of five categories: (1) status, change, and trends; (2) relationships between pressures or drivers of landscape conditions, changes, or trends and base biophysical conditions; (3) vulnerability and risk analysis; (4) forecasting; and (5) alternative future landscape analyses.

Status, Change, and Trends

Numerous landscape-based assessments of environmental status have been conducted at a range of scales for a relatively large number of environmental themes or issues using land cover and other biophysical data. These include assessments of forest fragmentation (Riitters et al. 2000, 2002), urbanization (Galleo et al. 2004), agricultural sustainability (Reuter et al 2002), road distribution and density (Watts et al. 2007), bird distribution (O'Connor et al. 1996), biological diversity (Zurlini 1999, Magura et al. 2001, Scott et al. 2003, Burkhardt et al. 2004), watershed condition or health (Walker et al. 2002; Jones et al. 1997, 2006), water quality and quantity (Behrendt 1996, Wickham et al. 2000, Jones et al. 2001a, Smith et al. 2001), aquatic biological condition (Hale et al. 2004, Donohue et al. 2006), soil loss (Van Rompaey and Govers, 2002), and multiple environmental themes (Jones et al. 1997, 2007, Wickham et al. 1999). All of these studies depend on the development of wall-to-wall

biophysical data including land cover and application of metrics, indicators, and models (see later discussion).

When two or more dates of wall-to-wall biophysical data are available, it becomes possible to conduct change and trends analyses. The NOAA Coastal Change Analysis Program (C-CAP) has been conducting land cover change analysis of coastal regions over the past several years (http://www.csc.noaa.gov/crs/lca/ccap.html), and the program contributes substantially to the Multi-Resolution Land Characteristics Consortium (MRLC, see below).

Landscape-based change and trends assessments have been conducted on ecosystem productivity (Minor et al. 1999, Young and Harris 2005, Nash et al. 2006) and land cover (Griffith et al. 2003). Moreover, there have been numerous assessments of landscape change and potential consequences to specific environmental themes, including wildlife populations and habitat (Vogelmann 1995, Jones et al. 2001b, Theobald and Romme 2007), biological diversity (Saunders et al. 1991, Ojima et al. 1994, Kattan et al. 1994, Koopowitz, et al. 1994), and water quality and quantity (Mattikalli and Richards 1996, Jones et al. 2001a), and watersheds and forests (Lathrop et al. 2007). Numerous other landscape-based assessments have analyzed land cover and other biophysical changes with regard to specific environmental drivers or stressors (see next section). Findings associated with these types of assessments are critical to vulnerability and risk assessments, ecological forecasting, and alternative futures analysis (see later sections).

Land cover data for two dates (early 1990s and 2000s) for the conterminous US make it possible to conduct a similar landscape change analysis across the entire lower 48 states at relatively fine spatial scales (30 m). To facilitate change analysis between these data, the MRLC is reclassifying the early 1990s imagery using the algorithm that was used to classify the 2000 imagery (see Wickham et al. 2007 for an application of this approach). Nationally consistent change information is available for the conterminous U.S. (http://www.mrlc.gov). The MRLC has proposed future US-wide land cover databases on five-year intervals. Such a program would permit an unprecedented assessment of landscape trends and consequences to a range of ecological services and environmental themes. A national-scale, sample-based, landscape trends program was initiated by the USGS and partner agencies

and organizations in the late 1990s (Loveland et al. 2002). This program has already reported on key landscape transitions that have occurred over the time period from the early 1970s to the early 2000s (see Griffith et al. 2003). The results from this program will provide a good foundation upon which to build a wall-to-wall trends program (e.g., from future MRLC efforts). Finally, land cover change and trends offer the most comprehensive way to track and evaluate the consequences of surface changes on a wide range of landscape processes affecting important ecological goods and services.

Relationships between Pressures/Drivers and Condition, Changes, and Trends

Quantifying linkages between environmental pressures and drivers (e.g., population change, road and energy development, increased, and water use) and landscape conditions and change is essential for understanding threats to and vulnerabilities of a wide range of environmental values and ecological services. This is also critical in formulating alternative future landscape scenarios to protect and improve environmental conditions. Some assessments involve retrospective or historical analysis of landscape change and pressures in an attempt to understand important drivers of landscape change (Mattikalli and Richards 1996, Wickham et al. 2000b, 2007, Jennings and Jarnagin 2002, Hostert et al. 2003, Wamelink et al. 2003), whereas some establish relationships from spatial patterns derived from single data layers (Wade et al. 2003). Others use rule-based and empirical models to evaluate the consequences of historical change (Hernandez et al. 2003). For example, Jones et al. (2001b) assessed the consequences of land cover change across the five-state, Mid-Atlantic region by creating a historical land cover database for the early 1970s from Landsat Multi-Spectral Scanner data, and applying a combination of empirical and rule-based models related to land-based nitrogen export and bird habitat quality. Land cover was a key component of both models and extrapolation to the regional scale. The most robust quantitative relationships are created when changes in land cover and biophysical data can be linked to changes in important environmental response variables (see later discussion).

Vulnerability and Risk Assessments

Existing spatial data, indicators, and models of pressures and states can be used to assess relative

vulnerability and risks of habitats and areas to future decline in overall environmental quality due to a combination of pressures (Wickham et al. 1999, Bradley and Smith 2004, Zurlini et al. 2004, Theobald and Romme 2007). These approaches generally involve integration of multiple biophysical databases, including land cover. Vulnerability can be assessed by integrating (in a spatially explicit manner) landscape classifications of resilience or sensitivity (based on inherent biophysical conditions), current conditions, and current levels of pressures or stresses (Bradley and Smith 2004). Vulnerability also can be assessed by modeling future landscape changes (Claggett et al. 2004, Theobald and Romme 2007). Future change models are often constructed from knowledge of historical patterns of change and drivers. Results of spatially explicit landscape change are then intersected with distributions of sensitive and/or resilient resources and associated processes to evaluate potential vulnerability. When the probably of change can be estimated and intersected with estimates of sensitivity or resiliency, it is possible to assess risk (Allen et al. 2006).

Land cover and other biophysical and human demographic data have been used to evaluate vulnerability and risks related to natural hazards such as fire (Rollins et al. 2004), tsunamis and earthquakes (Wood et al. 2002), and flooding (Sanders et al. 2006). These data also have been used to address vulnerability of specific geographic areas to spread of invasive species (Allen et al. 2006), and to evaluate distribution of and risks to Lyme disease (Jackson et al. 2006), and to assess environmental justice issues with regards to pollution exposure (Mennis 2005, Mennis and Jordan 2005).

Several organizations have embarked on broad-scale vulnerability assessment that involve the use of land cover and other biophysical data. These include the U.S Environmental Protection Agency's Regional Vulnerability Assessment Program (ReVA; Bradley and Smith 2004, http://www.epa.gov/reva/), the U.S. National Park Service's Watershed Condition Assessment Program (http://www.nature.nps.gov/water/ watershedconds.cfm), and the US Forest Service's Forests on the Edge Assessment (Stein et al. 2005).

Environmental Forecasting

When sampling networks permit the use of near-real time and seasonal data (e.g., climate and sat-

ellite data), it is possible to integrate these data with relatively static landscape data (e.g., slope, elevation, soil type) and process models to produce forecasts. For example, these types of data and models have been integrated to forecast crop yield (Reynolds et al. 2000, Kastens et al. 2001, Domenkiotis et al. 2004), species transitions (Peters et al. 2006), famine (Hutchinson 2001), risk of fire (Rollins et al. 2004), and vulnerability to continued urbanization (Kohiyama et al. 2004).

Examples of programs that integrate field and spatial data to conduct ecological forecasting include the Invasive Species Science Program (https://bp.gsfc.nasa.gov/ isfs.html), the US Forest Service's climate change atlas (Iverson et al. 1999, http://www.nrs.fs.fed.us/atlas/), NOAA's ecosystem forecasting program (see Valette-Silver and Scavia 2003, http://www.oceanservice.noaa.gov/topics/coasts/ecoforecasting/ welcome.html) and the Terrestrial Observation and Prediction System (http://www .ntsg.umt.edu/tops/). The Global Earth Observation System of Systems (GEOSS) offers significant potential to improve regional to global scale environmental forecasting, including water scarcity, drought, hazards, biodiversity, and food security (GEOSS 2005).

Alternative Landscape Futures and Conservation

When metrics, indicators, and models can be quantitatively linked and applied to spatial data, it becomes possible to assess the consequences and outcomes of management scenarios and activities that modify the land surface (Theobald and Hobbs 2002, Baker et al. 2004, Kepner et al. 2004). This generally involves a characterization of the current environment relative to one or several environmental themes and a series of workshops with the general public to identify a set of alternative future environments. Each alternative future scenario includes a set of spatially explicit management actions (or lack thereof) that influence the spatial elements and processes related to important environmental resources. Generally, there is a scenario that maintains the existing trend, one that promotes ecosystem or habitat conservation, and one that promotes maximum development or urbanization (White et al. 1997, Baker et al. 2004, Kepner et al. 2004, Voinov et al. 2004). Alternative futures analysis also may include a range of economic and policy scenarios that influence key processes and environmental themes (Wamelink et al. 2003 and Berger et al. 2004, respectively). The quality of these assessments

is dependent upon the quality of the data and models and the feasibility of the alternative future management scenarios. One of the great challenges to this approach is to generate effective and sustained public participation and ownership in the methods, scenarios, and results.

In some cases, landscape change models are used to forecast or project future landscape conditions given assumptions about rates and patterns of change in the models (Claggett et al. 2004, Theobald and Romme 2007). Specific management interventions are then assessed with regard to how they change projected landscape states and associated processes and environmental themes.

Landscape indicators and models can be used to identify and prioritize areas for conservation (Zhigal'skii et al. 2003). For example, land cover and other biophysical data, combined with rule-based habitat models, have been used to prioritize areas for conservation (Scott et al. 2003, Zurlini et al. 1999). At finer scales, landscape studies have been conducted to evaluate specific management options, for example, to evaluate the effectiveness of vegetation buffer strips in riparian zones (Borin et al. 2005). Additionally, landscape characterizations can be used to define areas where specific management systems might be most effective (Tenhunen et al. 2001, Jankauskas and Tiknius 2004).

KEY COMPONENTS OF LANDSCAPE-BASED ENVIRONMENTAL ASSESSMENTS

There are several aspects of environmental assessments where land cover and other biophysical data can play key roles. These include classification and characterization, metric and indicator development and application, and model development and application. Land cover and other biophysical data can provide an extrapolation framework for in-situ data on individual environmental themes of concern. This is primarily accomplished through classification schemes, indicators, and models (see below).

Classification and Characterization

A wide range of wall-to-wall biophysical data are used to classify and characterize geographic areas, including land cover, vegetation, soils, geology, topography (slope, aspect, land-form), stream networks, catchments (watersheds), climate (precipitation and temperature), and human population

and infrastructure (e.g. roads and dams). These data are used individually or in combination to characterize and classify landscapes, catchments, ecoregions, large basins, and entire countries relative to a wide range of terrestrial and aquatic environmental themes. Characterization and classification are used to: (1) reduce variance in potential indicator or metric response and interpretation (Angermeier et al. 2000), (2) identify reference conditions for different biophysical settings and classifications (Schmidtlein and Ewald 2003, Smith et al. 2003), (3) stratify areas for allocation of field samples and assist in sampling designs, especially in gradient studies (Ator et al. 2003), (4) help determine the applicability of various models based on differences in biophysical settings and classifications, (5) provide an extrapolation/up-scaling framework for models and indicators (Lenz 1999, Müller and Wiggering 1999, Djodjic et al. 2004, Running et al. 2004), (6) provide a hierarchical, down-scaling framework to predict potential ecosystem states (Detenbeck et al. 2000, Jongman et al., 2006), and (7) provide a spatial characterization and classification of the potential response of a specific geography to management alternatives and conservation … "capacity of the land" (Dobrowolska et al. 2004, Mucher et al. 2004, Wascher 2005). In some cases, there have been attempts to develop single classification systems to address all of these factors (Wickham and Norton 1994, Jensen et al. 2001, Jongman et al. 2006, Sayre et al. this volume). Classification and characterizations can be applied at several scales depending on the availability of spatial data. For example, community-level assessments rely on relatively high resolution spatial data, whereas countrywide assessments often involve use of coarser spatial data (Walker et al. 2002).

Most of these data are acquired from remote sensing, although some data such as human population, climate, and other field-based data are acquired from surveys and monitoring studies. Survey data usually come in the form of point or polygon summaries for administrative units or countries, and in some cases these summaries can be spatially interpolated via statistical methods such as kriging (Lloyd 2002). Some characterization approaches are conducted within an explicit spatial hierarchy of biophysical characteristics (Anderson 2000, Detenbeck et al. 2000, Mucher et al. 2003), some are conducted simply by overlaying biophysical data in a GIS without regard to a spatial hierarchy (Van Rompaey and Govers 2002), and some involve pattern classification derived from a single spatial

database (e.g., land cover, Wickham and Norton 1994). Results have to be evaluated within each particular classification and characterization framework adopted because when integrating or scaling data for different natural or administrative units the modifiable areal unit problem (MAUP) may introduce potential sources of error that can affect the results of spatial studies (Openshaw 1984). For example, this problem may arise when data are aggregated or generalized to specific assessment units (e.g., political or administrative boundaries), and then disaggregated or reapplied to different assessment units. The result is a misrepresentation of the original spatial variability in the data within and among the new assessment units.

Landscape Indicators

Indicator development is a critical step in the overall environmental assessment process. Land cover data are often a critical element of environmental metrics and indicators. For example, several important indicators in the "State of the Nation's Ecosystems Report" are based on land cover data (Heinz 2002). Moreover, national and continental-scale land cover projects, including the National Land Cover Database (NLCD) and Corine programs of the US and European Union, respectively, permit an analysis of changes in land cover-based metrics and indicators over huge geographic areas at relatively fine scales (30-100 m). Similar to other environmental indicators, landscape indicators are normally selected within a comprehensive monitoring framework, such as the Driver Pressure State Impact Response (DPSIR) framework (EU 1999, Müller et al. 2007; Figure 1).

Many different metrics can be generated from spatial data using geographic information systems (GIS). Landscape metrics include measures of composition (e.g., the percentage of specific land cover types), as well as pattern (e.g., natural land cover connectivity and the position of land cover types in a catchment). More recently metric development has included multiple spatial data (e.g., the amount of cropland on steep slopes derived from intersecting land cover and digital elevation model data, Jones et al. 1996; Figure 2). Additionally, new derivatives from the NLCD 2001 program now make it possible to estimate impervious surfaces and canopy cover over the conterminous US at 30 m resolution.

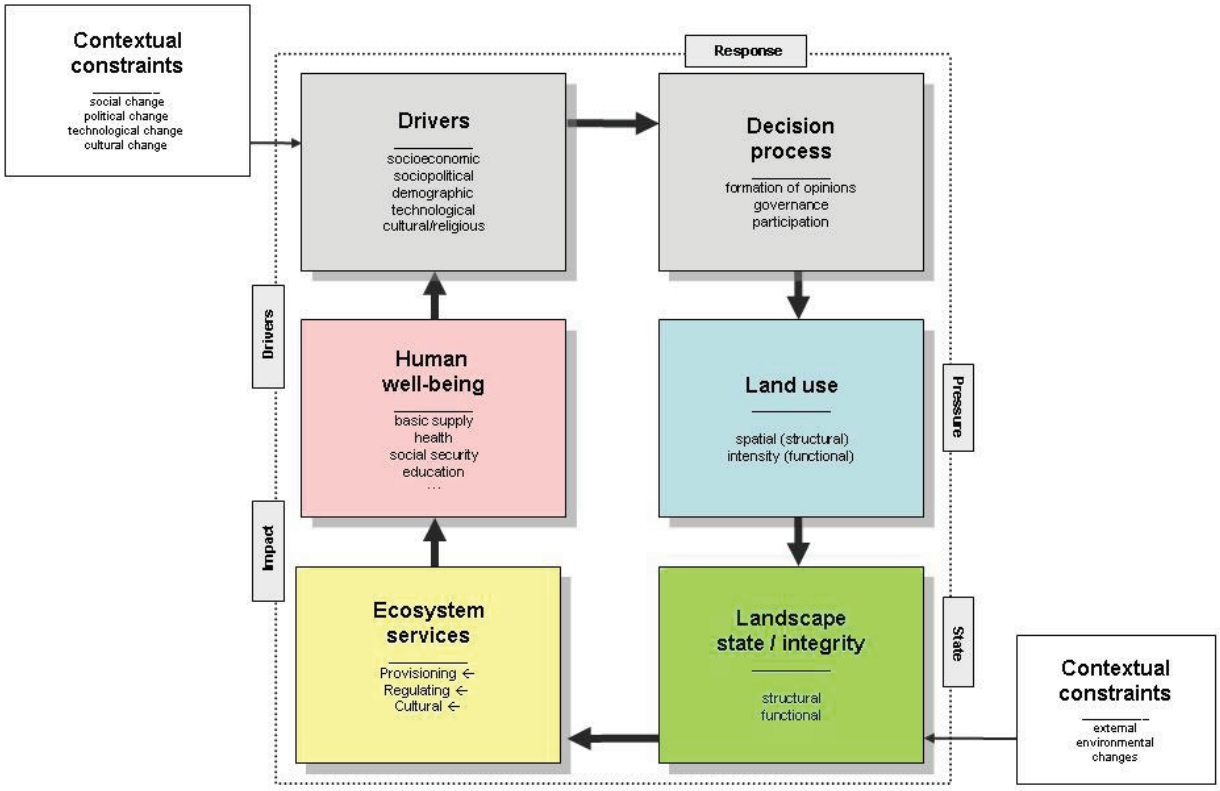


Figure 1. The Driver-Pressure-State-Impact-Response (DPSIR) indicator framework adopted by the European Union (EU 1999) and modified by Müller et al. 2007. Land cover and biophysical data play important roles in evaluating landscape state, change, pressures, and potential management responses (through Alternative Futures Analysis).

Metric development also may involve analysis of new analytical approaches to evaluate landscape composition and pattern (Riitters et al. 2000), and to measure natural and anthropogenic pressures over large areas (Imhoff et al. 1998, Steinhardt et al. 1999, Elvidge et al. 2001, Slonecker et al. 2001, Kohiyama et al. 2004, Longcore and Rich 2004). Metric studies also include analysis of colinearity and correlation among landscape metrics (Riitters et al. 1995). Generally, a metric is selected and used if spatial data are available to calculate the metric, and because qualitative relationships have been established between environmental themes (e.g., species diversity) and specific landscape composition and pattern. A landscape metric becomes an indicator when qualitative and quantitative relationships are established (Jones et al. 1996). In this way the metric becomes an indicator or surrogate of important biophysical processes, ecological states, or pressures. This is accomplished through findings from existing studies, or through new studies involving biophysical, ecological state, or pressure (stressor) gradients (Ator et al. 2003). Where historical landscape data are available (e.g., aerial photography),

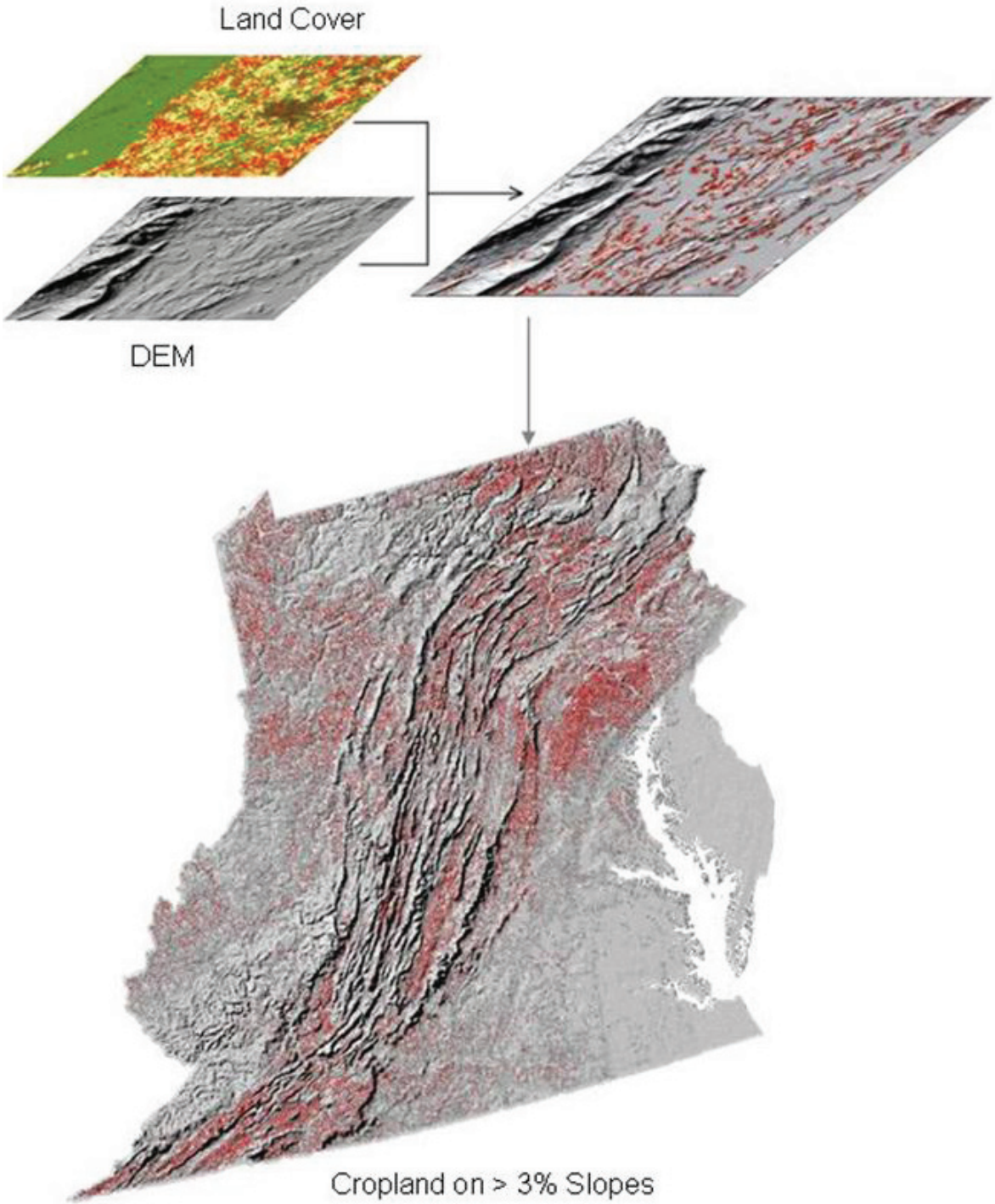


Figure 2. Intersection of 30 m slope and land cover databases to yield a metric of cropland on greater than 3 percent slope, an indicator of potential soil and nutrient loss, across the five-state area of the US Mid-Atlantic Region. Intersection of biophysical data play an important role in evaluating landscape conditions and processes over broad regions.

it may be possible to develop quantitative relationships between a particular pressure (e.g., impervious surfaces) and a state or process (e.g., stream flow and discharge, Jennings and Jarnagin 2002). In the example illustrated in Figure 3, a small watershed in Fairfax County Virginia increased from approximately 3 to 34 percent impervious surface. The result was an increase in mean daily flow, an increase in maximum flow, and an increase in the frequency of bank to bank disturbance events (Jennings and Jarnagin 2002). For this watershed, it takes 45 fewer mm of rain (from 140 to 95 mm) to achieve bank-to-bank flow levels. Increased magnitude and frequency of disturbance events , such as those generated by the increased floods, have been hypothesized to negatively influence surface water habitat and biological conditions (Slonecker 2001).

Metric and indicator development also can include a wide range of remote sensing research and applications (Victorov 1999). This includes derivation of landscape composition and pattern from archival and existing imagery such as Landsat (Tucker et al. 2004), evaluation of relatively new, high resolution spectral (e.g., hyperspectral, Shippert 2003) and spatial (e.g., IKONOS, Vina et al. 2003) imagery, analysis of canopy and vertical vegetation structure (e.g., LiDAR, Anderson et al. 2006, Streutker and Glenn 2006), more direct measures of ecological process variables (e.g., net primary productivity, Running et al. 2004), and landscape change detection (Sohl et al. 2003, Victorov et al. 2004). More detailed information on land cover composition and structure can improve the interpretability of landscape indicators and models.

Spatial filtering (Riitters et al. 1997) and morphological image processing (Vogt et al. 2007a, b) provide other ways to measure landscape metrics and levels of fragmentation or connectivity at multiple scales across broad geographic areas. Furthermore, they provide flexible ways to evaluate scale and emergent spatial properties in land cover imagery.

One of the goals of indicator development is to establish a set or suite of indicators that, in total, reflect ecological pressures, states, impacts, and responses (see Figure 1). When a common and internally consistent set of spatial data is available over large geographic areas, landscape metrics and indicators can be generated and used to estimate and compare ecological states, pressures, and impacts across broad regions (Jones et al. 1997, Wickham et al. 1999).

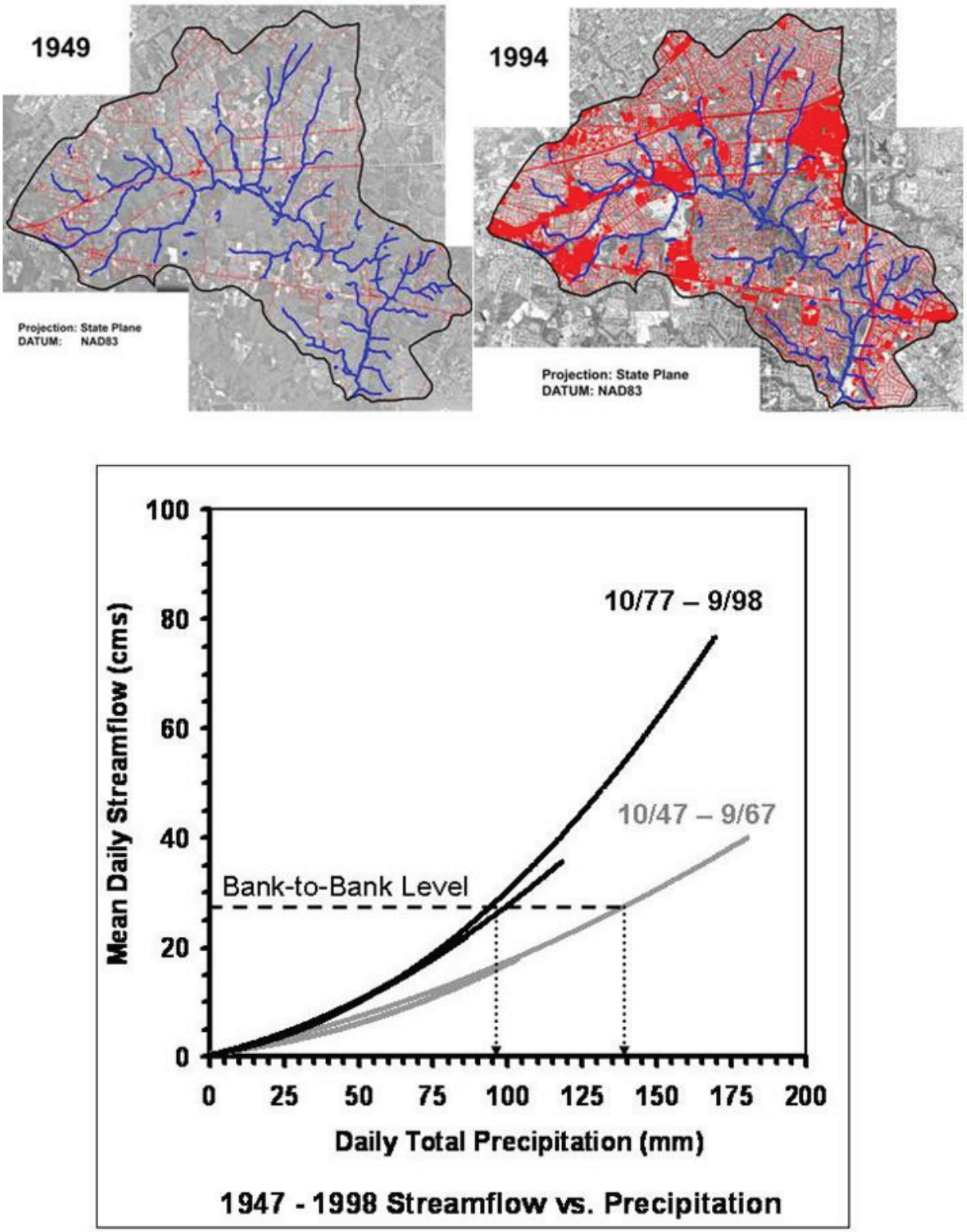


Figure 3. The impact of increasing impervious surface on peak flow events in a Fairfax, County US watershed (modified from Jennings and Jarnagin 2002).

Some assessments require only one or a few spatial databases to generate metrics and indicators, whereas others require multiple spatial databases. For example, Riitters et al. (2000) and Wade et al. (2003) assessed forest fragmentation at the global scale by applying a forest fragmentation metric to digital land cover data. Jones et al. (1997, 2008) assessed multiple environmental themes across the US and Europe, respectively, that required acquisition and use of several spatial databases. Finally, the complexity of metrics used in assessments varies depending on whether the goal of the assessment is for targeting and prioritization (Steinhardt et al. 1999, Wickham et al. 2000, Bradley and Smith 2004) or forecasting or prediction (Reynolds et al. 2000); the former generally uses more qualitative approaches (e.g., metrics, indicators, and simply models), whereas the latter generally relies on more quantitative approaches and complex models.

Landscape Models

Land cover and other biophysical data are often critical elements in spatially distributed models, but especially those related to habitat quality and distribution, water quality, soil loss, and nutrient export. The development of these models is crucial in extending (scaling) in-situ measures to large basins and regions.

Generally, two types of models are used in landscape assessments: empirical models and process models. Empirical models involve quantifying relationships between landscape/biophysical characteristics and patterns (landscape metrics) and measures of environmental values (e.g., bird species richness) or pressures (e.g., nutrient export or loadings). Generally, these studies involve pairing landscape and biophysical metrics measured on spatial supporting units (e.g., a catchment) with field samples (e.g., water quality samples; Jones et al. 2001b, Smith et al. 2001, Iankov et al. 2004). In some cases, landscape metrics are calculated at several scales surrounding field samples (e.g., headwater areas, riparian zones, catchment scale). The goal is to quantify relationships between environmental values of interest and landscape/biophysical composition and pattern through multivariate and other statistical approaches and then apply the statistical function across the larger area via the wall-to-wall data. Other statistical approaches, such as Maximum Entropy, Genetic Algorithm for Rule-set

Predictions (GARP), and Regression Tree Analysis, can be used to model species' distributions and to evaluate uncertainty in those estimates (Stockwell and Peters 1999, Garzon et al. 2006, Phillips et al. 2006). These approaches use in-situ, species-presence data as well as several spatially continuous biophysical databases including land cover. The result is an ability to estimate pressure, state, or impacts over a broader area, including areas where no samples exist. In some cases, markedly different biophysical and/or human use settings across a large region or basin require development and testing of different models. Additionally, it is often difficult to match the spatial and temporal scales of landscape processes and patterns with scales represented by data collected on environmental themes and associated variables at the site or field scale (Skoien et al. 2003).

Most empirical studies trade spatial variability for time to develop quantitative linkages between in-situ and wall-to-wall biophysical data, primarily due to limited temporal coverage of in-situ measures on environmental themes or processes of interest. This approach has been used to model bird habitats and populations (O'Connor et al. 1996, Jones et al. 2000, O'Connell et al. 2000), water quality (Jones et al. 2001b, 2006), and stream biological condition (Donohue et al. 2006). However, powerful relationships have been developed using historical landscape change and stream flow data (see Jennings and Jarnagin 2002).

A critical element of empirical studies is data from in-situ monitoring networks, such as the USGS National Stream Gauge Network (http://waterdata.usgs.gov/nwis), the USGS National Water Quality Assessment Program (NAWQA, http://water.usgs.gov/ nawqa/), the North American Breeding Bird Survey (BBS, http://www.pwrc.usgs.gov/ BBS/), the Environmental Monitoring and Assessment Program (EMAP, http:// www.epa.gov/emap/), the Forest Inventory and Analysis (FIA, http://fia.fs.fed.us/) Program, and the Natural Resource Inventory (NRI, http://www.nrcs.usda.gov/ technical/NRI/).

The other modeling approach involves the development of rule-based or process-based models. Important variables and functions for these models are generally derived from intensive studies at fine scales from existing literature, or from expert opinion. The goal in applying these models is to develop transfer functions (quantitative relationships or functions) between the model parameters and wall-to-wall landscape data. For example, estimation of soil loss over large geographic areas is pos-

sible because soil texture (a surrogate for erosivity …an important parameter in soil loss models) is an attribute in many of the digital soils databases (Van Rompaey and Govers 2002). Similarly, detailed studies have established nutrient export coefficients for different land cover types, and when these data are combined with digital land cover, it is possible to identify areas where surface waters may be impaired by excess nutrients and sediments (Wickham et al. 2000). Similarly, non-point source and point-source nutrient loads can be combined to estimate total nutrient loads into water bodies (Behrendt 1996, Kondratyev et al. 2004).

Two key issues in process model implementation are the number of parameters that go into the model and the ability to transfer key functions to wall-to-wall spatial data, including land cover. If there are too many parameters in a model, then it is difficult to apply the model over broad areas because spatial data and transfer functions are often not available for a large number of process-related parameters. However, if parameters are over-simplified and there are too few of them, then the model may fail to capture important differences in the landscape (Van Rompaey and Govers 2002), especially for relatively small areas (e.g., small catchments). The key is to develop and apply models that take into consideration the types of questions and the levels of complexity and scales that result from the types of questions being asked. Many regional- and basin-scale habitat and water quality models involving few parameters are good at targeting and prioritizing areas needing further study or potential management intervention (coarse filter, Bradley and Smith 2004), whereas more parameter-intensive models are used at local scales to evaluate local conditions and site-specific management solutions. These models often require finer-scale land cover data than those available at regional and national scales (e.g., the NLCD).

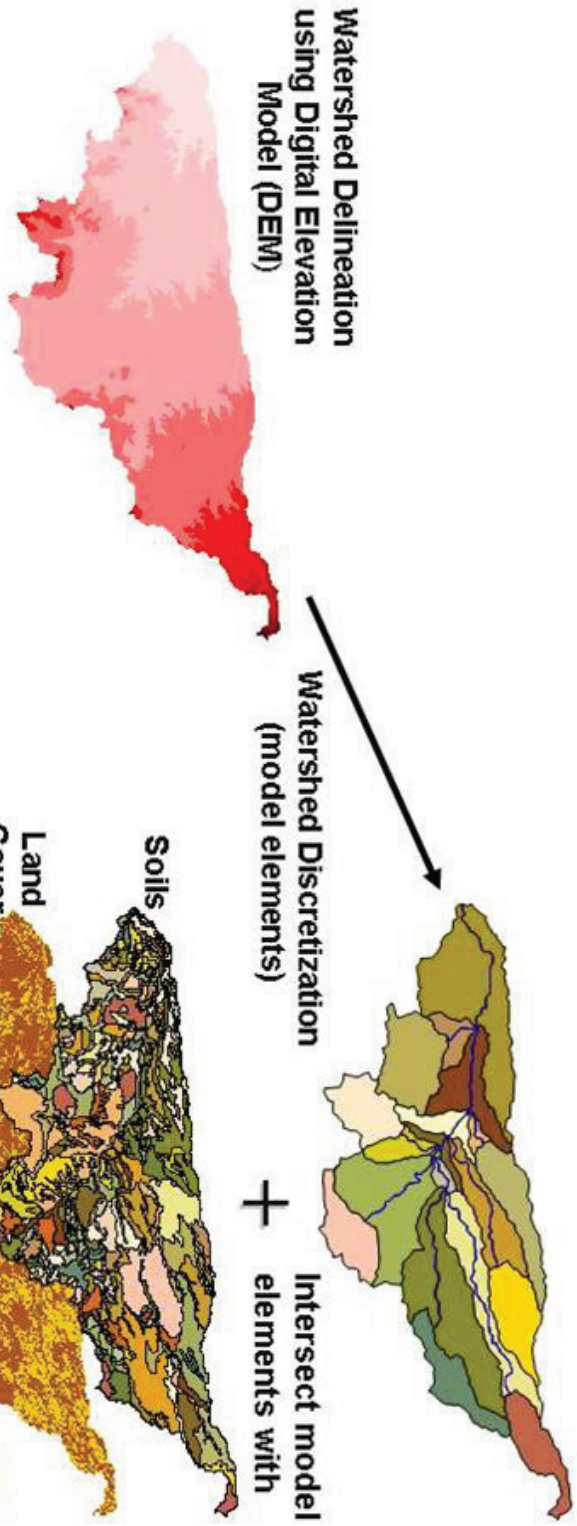
Land cover has been used to model habitat suitability for a range of species over broad scales (Riitters et al. 1997, Zurlini et al. 1999, Atauri et al. 2001, Scott et al. 2003, Tuller et al. 2004). This generally involves applying a habitat suitability rule to land cover, soil, topographical, and/or climate data. Additionally, models have been developed and applied to remote sensing and other spatial data to evaluate fundamental ecosystem processes, including forest transpiration and photosynthesis (Anselmi et al. 2004), evapotranspiration and soil water dynamics (Wegehenkel et al. 2001), fire and

disturbance frequency (Keane et al. 2002, Rollins et al. 2004), and run-off, sedimentation, and water quality. Land cover (e.g., NLCD) has been used in combination with US Census data to model environmental justice issues across broad geographic areas (Mennis 2005, Mennis and Jordan 2005). Figure 4 illustrates the Automated Geospatial Watershed Assessment (AGWA) modeling tool (Miller et al. 2007). This is a GIS-based process model that evaluates the impact of land cover change on hydrologic processes affecting run-off and sediment transport.

Assessment Units

Because of the wide range of environmental themes, issues, and questions being addressed by environmental managers, landscape assessments can potentially occur at a many different spatial scales on a range of political and environmental classification units. The size of the assessment area can vary between small catchments or habitat areas (Dunjo et al. 2004) on up to entire regions, basins, and continents (Lorenz et al. 1999, Riitters et al. 2000, Walker et al 2002, Galleo et al. 2004). Finer-scale assessments generally involve the use of higher resolution spatial and field data (for example, data on vegetation structure, plant species type, etc), whereas broader-scale assessments generally involve readily available spatial data (e.g., 30 m).

Landscape assessments also involve the use of spatial data representing natural (e.g., ecoregions and catchments) and political (e.g., provinces, states, political regions, countries) boundaries. Ecoregion boundaries are created through multi-scaled characterization of biophysical characteristics (see earlier section) and catchments through the use of stream network and/or elevation data to determine the boundaries and direction of flow through a landscape. Both natural and political boundary data come in the form of digital layers that can be integrated (via a GIS) with landscape and other biophysical data to calculate indicators and implement models on specific units. When the goal of the assessment is simply to represent spatial variability in indicator and model results on a map, GIS-generated grid cells are often used (Jones et al. 2001a, Wickham et al. 2002). Additionally, assessments are conducted on buffer zones around riparian zones (Borin et al. 2005, Baker et al. 2006), surface waters, including estuaries (Hale et al. 2004), and other features (e.g., hazardous waste sites). Buffer zone



KINEROS Outputs	*SWAT Outputs*
Channel Infiltration (m^3/km)	Precipitation (mm)
Plane Infiltration (mm)	ET (mm)
Runoff (mm or m^3)	Percolation (mm)
Sediment yield (kg)	Channel Disch. (m^3/day)
Peak flow (m^3/s or mm/hr)	Transmission loss (mm)
Channel Scour (mm)	Water yield (mm)
Sediment discharge (kg/s)	Sediment yield (t/ha)

Figure 4. The Automated Geospatial Watershed Assessment (AGWA) tool. The tool integrates land cover and biophysical data to estimate water-related characteristics important to environmental managers and planners.

assessments require spatial data layers on streams, estuaries, other surface waters, or the landscape feature of interest.

Landscape Assessment Tools

Several GIS extensions and models have been developed that permit assessment of environmental resources and processes over a variety of scales. These extensions and models use a variety of readily available spatial data. Some calculate landscape metrics and simple models at a variety of scales (McGarigal et al. 2002, Ebert and Wade 2004), whereas some model the influence of landscape pattern and change on specific environmental resources and associated processes, including water and hydrology (Engel et al. 2003, Hernandez et al. 2003, Miller et al. 2007), forest succession and disturbance (Mladenoff 2004), and habitat (Schumaker 1998, Akcakaya 2000). These types of software and tools accept readily available landscape data and permit assessments at a variety of scales.

CONCLUSIONS

Land cover and other biophysical data play key roles in environmental assessments. They provide basic data on spatially explicit patterns of landscape features and associated processes that affect fluxes of biota, water, energy, and materials. When these data are related spatially and temporally they can provide the basic elements for modeling fundamental environmental processes at a range of scales. As such, they provide a framework for extrapolation of in-situ data to make assessments of environmental conditions and changes over broad geographic areas.

As finer-scale biophysical data become increasingly available, it will become possible to apply landscape metrics and models at local and community levels and to relate conditions at those scales to broader catchment and basin scales. Moreover, synthesis of data from sensors with different spatial and temporal resolution will improve our ability to track more frequent changes in land-surface condition (e.g., land cover patch quality and photosynthetic activity), as well as vertical structure and composition (e.g., canopy height by life form and species). This will improve our ability to track land-surface changes in response to major drivers such as climate change, and to relate those changes

to important ecological services. New and enhanced statistical and modeling approaches will also improve estimates of land-surface changes and our ability to interpret consequences and opportunities for conservation.

New national and continental scale land cover change products, such as that offered by the MRLC, provide for an unprecedented opportunity to assess the potential consequences of landscape change on a wide range of ecological services. However, it is imperative to protect and expand spatially comprehensive and consistent in-situ monitoring programs, such as the USGS stream gauge network,

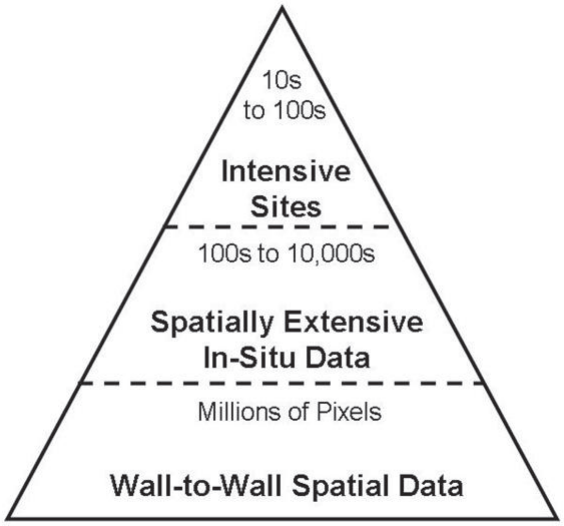


Figure 5. The three-tiered monitoring and assessment framework of the US Committee on Environment and Natural Resources (CENR, 1997). The framework emphasizes the importance of land cover and other biophysical data (base of tier), as well as in-situ monitoring data.

NAWQA, EMAP, NRI, and FIA. These programs provide the base in-situ data from which landscape models and indicators are derived, and form the critical middle component of the US Committee on Natural Resources and the Environment (CENR) monitoring framework (Figure 5). New research and monitoring programs, including the National Ecological Observatory Network (NEON, http://www.neoninc.org/) and the National Phenology Network (http://www.usanpn.org), offer significant potential to develop multi-scale landscape models and to demonstrate the multi-tiered approach recommended by the CENR.

ACKNOWLEDGEMENTS

I am grateful to the US Geological Survey and several other agencies and organizations for sponsoring the National Land Cover Summit, and to S. Taylor Jarnagin (US EPA), Don Weller (The Smithsonian Environmental Research Center), John Wiens (The Nature Conservancy), and Dave Theobald (Colorado State University) for thoughtful comments and suggestions on earlier versions of this manuscript.

REFERENCES

Akcakaya, H.R. 2000. Population viability analyses with demographically and spatially structured models. *Ecological Bulletins* 48:23-38.

Allen, C.R., A.R. Johnson, and L. Parris. 2006. A framework for spatial risk assessments: potential impacts of nonindigenous invasive species on native species. *Ecology and Society* 11:39 http://www.ecologyandsociety.org/vol11/iss1/art39/

Anderson, M. 2000. Ecological land units in the central Appalachians Ecoregions (CAP). Pp. A6-1 – A6-4, in Groves, C., Valutis, L, Vosick, D., Neely, B., Wheaton, K., Touval, J. and Runnels, B. (eds.), Designing geography of hope: a practioner's handbook for ecoregional conservation planning, Volume 2, The Nature Conservancy, Arlington, Virginia USA.

Anderson, J., M.E. Martin, M-L Smith, R.O. Dubayah, M.A. Hofton, P. Hyde, B.E. Peterson, J.B. Blair, and R.G. Knox. 2006. The use of waveform lidar to measure northern temperate mixed conifer and deciduous forest structure in New Hampshire. *Remote Sensing of Environment* 105:248-261.

Angermeier, P.L., R.A. Smogor, and J.R. Stauffer. 2000. Regional frameworks and candidate metrics for assessing biotic integrity in Mid-Atlantic Highland streams. *Transactions of the American Fisheries Society* 129:962-981.

Anselmi, S., M. Chiesi, M. Giannini, F. Manes, and F. Maselli. 2004. Estimation of Mediterranean forest transpiration and photosynthesis through the use of an ecosystem simulation model driven by remotely sensed data. *Global Ecology and Biogeography* 13:371-380.

Atauri, J.A., and J.V. de Lucio. 2001. The role of landscape structure in species richness distribution of birds, amphibians, reptiles, and lepidopterans in Mediterranean landscapes. *Landscape Ecology* 16:147-159.

Ator, S.W., A.R. Olsen, A.M. Pitchford, and J.M Denver. 2003. Application of a multipurpose unequal probability stream survey in the Mid-Atlantic Coastal Plain. *Journal of American Water Resources Association* 39:873-885.

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.

Baker, M.E., D.E. Weller, and T.E. Jordan. 2006. Improved methods for quantifying potential nutrient interception by riparian buffers. *Landscape Ecology* 21:1327-1345.

Behrendt, H. 1996. Inventories of point and diffuse sources and estimated nutrient loads – a comparison for different river basins in central Europe. *Water Science Technology* 33:99-107.

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

Borin, M., M. Vianello, F. Morari, and G. Zanin. 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. *Agriculture, Ecosystems and Environment* 105:101-114.

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

Burkhardt, B., F. Müller, and T. Kumpula. 2004. Integrative assessment of different reindeer management strategies in North Finland. *EcoSys Suppl*. Bd. 42:60-66.

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.

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.

Detenbeck, N.E., S.L. Batterman, V.J. Brady, J.C. Brazner, V.M. Snarski, D.K. Taylor, J.A. Thompson, and J.W. Arthur. 2000. A test of watershed classification systems for ecological risk assessment. *Environmental Toxicology and Chemistry* 19:1174-81.

Djodjic, F., K. Borling, and L. Bergstrom. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. *Journal of Environmental Quality* 33:678-684.

Dobrowolska, J. 2004. GIS – effective support in water resource management and protection. *EcoSys Suppl.* Bd. 42:71-89.

Domenikiotis, C., M. Spiliotopoulos, E.Tsiros, and N.R. Dalezios. 2004. Early cotton production assessment in Greece based on a combination of the drought Vegetation Condition Index (VCI) and the Bhalme and Mooley Drought Index (BMDI). *International Journal of Remote Sensing* 25:5373-5388.

Donohue, I., M.L. McGarrigle, and P. Mills. 2006. Linking catchment characteristics and water chemistry with the ecological status of Irish rivers. *Water Research* 40:91-98.

Dunjo, G., G. Pardini, and M. Gispert. 2004. The role of land use-land cover on runoff generation and sediment yield at a microplot scale, in a small Mediterranean catchment. *Journal of Arid Environments* 57:239-256.

Ebert, D.W., and T.G. Wade. 2004. Analytical Tools Interface for Landscape Assessments (ATtILA): Users Manual. U.S. Environmental Protection Agency Report # EPA/600/R-04/083, Washington, D.C USA

Elvidge, C.D., M.L. Imhoff, K.E. Baugh, V.R. Hobson, I. Nelson, J. Safran, J.B. Dietz, and B.T. Tuttle. 2001. Night-time lights of the world: 1994-1995. *Journal of Photogrammetry and Remote Sensing* 56:81-99.

Engel, B.A., J. Choi, J. Harbor, and S. Pandey. 2003. Web-based DSS for hydrologic impact evaluation of small watershed land use changes. *Computers and Electronics in Agriculture* 39:241-249.

EU (European Union). 1999. Towards environmental pressure indicators for the EU. First Edition, Communication from the Commission to the Council and the European Parliament on Directions for the EU on Environmental Indicators and Green National Accounts. (COM 94/670).

Galleo, K.P., C.D. Elvidge, L. Yang, and B.C. Reed. 2004. Trends in night-time city lights and vegetation indices associated with urbanization within the conterminous USA. *International Journal of Remote Sensing* 25:2003-2007.

Garzon, M.B., R. Blazekb, M. Neterlerb, R.S. de Diosa, H.S. Olleroa, and C. Furlanellob. 2006. Predicting habitat suitability with machine learning models: The potential area of *Pinus sylvestris* L. in the Iberian Peninsula. *Ecological Modeling* 197:383-393.

GEOSS (Global Earth Observation System of Systems). 2005. The Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan. http://earthobservations.org/ .

Griffith, J.A., S.V. Stehman, and T.R. Loveland. 2003. Landscape trends in Mid-Atlantic and Southeastern United States ecoregions. *Environmental Management* 32:572-588.

Hale, S.S., J.F. Paul, and J.F. Heltshe. 2004. Watershed landscape indicators of estuarine benthic condition. *Estuaries* 27:283-295.

Heinz Center (The H. John Heinz Center). 2002. The State of the Nation's Ecosystems. New York: Cambridge University Press, 288p.

Hernandez, M., W.G. Kepner, D.J. Semmens, D.W. Ebert, D.C. Goodrich, and S.N. Miller. 2003. Integrating a landscape/hydrologic analysis for watershed assessment. Pp. 461-466, in Renear, K.G., McElroy, S.A., Gburek, W.J., Canfield, E.H., and Scott R.L. (eds.), First Interagency Conference on Research in Watersheds, October 27-30, 2003. U.S. Department of Agriculture, Agricultural Research Service, Tucson, Arizona, USA.

Homer C, C. Huang, L.Yang , B. Wylie, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing* 70:829-840.

Hostert, P., A. Roder, J. Hill, T. Udelhoven, and G. Tsiourlis. 2003. Restrospective studies of grazing-induced land degradation: a case study in central Crete, Greece. *International Journal of Remote Sensing* 24:4019-4034.

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

Iankov, S., M. Nikolova, and S. Nedkov. 2004. Use of bioindicators for landscape assessment in the Yantra Basin, Central North Bulgaria. *EcoSys Suppl.* Bd. 42:35-49.

Imhoff, M.L., D. Stutzer, W.T. Lawrence, and C. Elvidge. 1998. Assessing the impact of urban sprawl on soil resources in the United States using nightime "City Lights" satellite images and digital soils maps. Chapter 3, in Sisk, T.D. (ed.), Perspectives on the land-use history of North America: a context for understanding our changing environment. U.S. Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR 1998-0003.

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., J.F. Levine, and E.D. Hilborn. 2006. A comparison of analysis units for associating Lyme disease with forest-edge habitat. *Community Ecology* 7:189-197.

Jankauskas, B., and A. Tiknius. 2004. Sustainable and environmental-friendly land use systems for undulating reliefs of the temperate climate zone. *EcoSys Suppl.* Bd. 42:50-59.

Jennings, D.B. and S.T. Jarnagin. 2002. Impervious surfaces and stream flow discharge: a historical perspective in a Mid-Atlantic subwatershed. *Landscape Ecology* 17:471-489.

Jensen, M.E., I.A. Goodman, P.S. Bourgeron, N.L. Poff, and C.K. Brewer. 2001. Effectiveness of biophysical criteria in the hierarchical classification of drainage basins. *Journal of the American Water Resources Association* 37:1155–1167.

Jones, K.B., J. Walker, K.H. Riitters, J.D. Wickham, and C. Nicoll. 1996. Indicators of Landscape Integrity, pp. 155-168, in J. Walker and Reuter, D.J. (eds.), Indicators of catchment health: a technical perspective. CSIRO Publishing, Victoria, Australia.

Jones, K.B., K.H. Riitters, J.D. Wickham, R.D. Tankersley, Jr., R.V. O'Neill, D.J. Chaloud, E.R. Smith, and A.C. Neale. 1997. *An Ecological Assessment of the United States Mid-Atlantic Region: A Landscape Atlas.* EPA/600/R-97/130.

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.

Jones, K.B., A.C. Neale, T.G. Wade, J.D. Wickham, C.L. Cross, C.M. Edmonds, T.R. Loveland, M.S. Nash, K.H. Riitters, and E.R. Smith. 2001b. The consequences of landscape change on ecological resources: an assessment of the United States Mid-Atlantic Region, 1973-1993. *Ecosystem Health* 7:229-242.

Jones, K.B., A.C. Neale, T.G. Wade, C.L. Cross, J.D. Wickham, M.S. Nash, C.M. Edmonds, K.H. Riitters, R.V. O'Neill, E.R. Smith, and R. Van Remortel. 2006. Multiscale relationships between landscape characteristics and nitrogen concentrations in streams. Pp. 205-224, in Wu, J., Jones, K.B., Li, H., Loucks, O.L (eds.), Scaling and Uncertainty Analysis in Ecology: Methods and Applications. Springer, The Netherlands.

Jones, K.B., M.S. Nash, T.G. Wade, J. Walker, A.C. Neale, F. Müller, G. Zurlini, N. Zaccarelli, S. Hamann, R. Jongman, S. Nedkov, W.G. Kepner, and C.G. Knight. 2007. Cross-European landscape analyses: illustrative examples using existing spatial data. Pp. 258-316, in Petrosillo, I et al. (eds.), Use of Landscape Sciences for the Assessment of Environment Security. Springer, in press.

Jongman, R.H.G., R.G.H. Bunce, M.J. Metzger, C.A. Mucher, D.C. Howard, and V.L. Mateus. 2006. Objectives and applications of a statistical environmental stratification of Europe. *Landscape Ecology* 21:409-419.

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.

Kattan, G.H., H.Alvarez-Lopez, and M. Giraldo. 1994. Forest fragmentation and bird extinctions: San Antonio eighty years later. *Conservations Biology* 9:138-146.

Keane, R.E., M.G. Rollins, C.H. McNicoll, and R.A. Parsons. 2002. Integrating ecosystem sampling, gradient modeling, remote sensing, and ecosystem simulation to create spatially explicit landscape inventories. USDA Forest Service Gen Tech. Report RMRS-GTR-92, Fort Collins, Colorado, USA.

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.

Kohiyama, M., H. Hayashi, N. Maki, M. Higashida, H.W. Kroehl, C.D. Elvidge, and V.R. Hobson. 2004. Early damaged area estimation system using DMSP-OLS night-time imagery. *International Journal of Remote Sensing* 25:2015-2036.

Kondratyev, S.A., A.I. Moiseenkov, and A.V. Izmailova. 2004. Catchment modelling and land cover change impacts on runoff and substance wash out. *EcoSys Suppl.* Bd. 42:16- 28.

Koopowitz, H., A.D. Thornhill, and M. Anderson. 1994. A general stochastic model for the prediction of biodiversity losses based on habitat conservation. *Conservation Biology* 8:425-438.

Lathrop, R.G., D.L. Tulloch, and C. Hatfield. 2007. Consequences of land use change in the New York – New Jersey highlands, USA: landscape indicators of forest and watershed integrity. *Landscape and Urban Planning* 79:150-155.

Lenz, R.J.M. 1999. Landscape health indicators for regional eco-balances. Pp. 12-23, in Pykh, Y.A., Hyatt, D.E., Lenz, R.J.M (eds.), Environmental Indices: Systems Analysis Approach, EOLSS Publishers Co. Ltd., London, England.

Lloyd, C. D. 2002. Increasing the accuracy of predictions of monthly precipitation in Great Britain using kriging with an external drift. Pp. 243-267, in G. M. Foody and Atkinson, P.M. (eds.), Uncertainty in Remote Sensing and GIS, John Wiley and Sons, New York.

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

Loveland, T.R., T.L. Sohl, S.V. Stehman, A.L. Gallant, K.L. Sayler, and D.E. Napton. A strategy for estimating the rates of recent United States land-cover changes. 2002. *Photogrammetric Engineering and Remote Sensing* 68:1091-1099.

Lorenz, C.M., A.J. Gilbert, and W.P. Cofino. 1999. Indicators for transboundary river basin management. Pp. 313-328, in Pykh, Y.A., Hyatt, D.E., Lentz, RJ.M (eds.), Environmental Indices: Systems Analysis Approach, EOLSS Publishers Co. Ltd., London, England.

Magura, T., V. Kodobocz, and B. Tothmeresz. 2001. Effects of habitat fragmentation on carabids in forest patches. *Journal of Biogeography* 28:129-138.

Mattikalli, N.M., and K.S. Richards. 1996. Estimation of surface water quality changes in response to land use change: application of the export coefficient model using remote sensing and geographic information system. *Journal of Environmental Management* 48:263-282.

McCollin, D. 1993. Avian distribution patterns in a fragmented wooded landscape (North Humberside, U.K.): the role of between-patch and within-patch structure. *Global Ecology and Biogeography Letters* 3:48-62.

McGarigal, K., S.A. Cushman, M.C. Nell, and E. Ene. 2002. FRAGSTATS: spatial pattern analysis program for categorical maps. http:/www.umass.edu/landeco/research/fragstats/fragstats.html.

Mennis, J.L. 2005. The distribution and enforcement of air polluting facilities in New Jersey. *The Professional Geographer* 57: 411–422.

Mennis, J.L., and L. Jordan. 2005. The distribution of environmental equity: exploring spatial nonstationarity in multivariate models of air toxic releases. *Annals of the Association of American Geographers* 95:249–268.

Miller, S.N., D.J. Semmens, D.C. Goodrich, M. Hernandez, R.C. Miller, W.G. Kepner, D.P Guertin. 2007. The Automated Geospatial Watershed Assessment tool. *Environmental Modeling and Software*. 22:365-377.

Minor, T.B., J. Landcaster, T.G. Wade, J.D. Wickham, W.G. Whitford, and K.B. Jones. 1999. Evaluating change in rangeland condition using multitemporal AVHRR data and geographic information system analysis. *Environmental Monitoring and Assessment* 59:211-223.

Mladenoff, D.J. 2004. LANDIS and forest landscape models. *Ecological Modeling* 180:7-19.

Mucher, C.A., R.G.H. Bunce, R.H.G. Jongman, J.A. Klijn, A.J.M. Koomen, M.J. Metzger, and D.M. Wascher. 2003. Identification and characterization of environments and landscape in Europe. Alterra Report Number 832, Wageningen, The Netherlands.

Mucher, C.A., R.G.H. Bunce, S.M. Hennekens, and J.H.J. Schaminee. 2004. Mapping European habitats to support the design and implementation of a Pan-European ecological network: the PENNHAB project. Alterra Report Number 952, Wageningen, The Netherlands.

Muller, F., and H. Wiggering. 1999. Environmental indicators determined to depict ecosystem functionality. Pp. 64-82, in Pykh, Y.A., Hyatt, D.E., Lentz, RJ.M (eds.), Environmental Indices: Systems Analysis Approach, London: EOLSS Publishers Co. Ltd.

Müller, F., K.B. Jones, K. Krauze, B.L. Li, I. Petrosillo, S. Victorov, G. Zurlini, and W.G. Kepner. 2007. Contributions of landscape sciences to the development of environmental security. Pp. 1-9, in Petrosillo, I et al. (eds.), Use of Landscape Sciences for the Assessment of Environment Security. Springer, in press.

Nash, M.S., T.G. Wade, D.T. Heggem, and J.D. Wickham. 2006. Does anthropogenic activities or nature dominate the shaping of the landscape in the Oregon pilot study area for 1990-1999? Pp. 305-323, in Kepner, W.G., Rubio, J.L., Mouat, D.A., and Pedrazzini, F. (eds.), Desertification in the Mediterranean Region: a Security Issue. Series C: Environmental Security, Vol. 3, Springer, The Netherlands.

O'Connell, T.J., R.E. Jackson, and R.P. Brooks. 2000. Bird guilds as indicators of ecological condition in the central Appalachians. *Ecological Applications* 10:1706-1721.

O'Connor, R.J., M.T. Jones, D. White, C. Hunsaker, T. Loveland, B. Jones, and E. Preston. 1996. Spatial partitioning of environmental correlates of avian biodiversity in the conterminous United States. *Biodiversity Letters* 3:97-110.

Ojima, D.S., K.A. Galvin, and B.L. Turner, II. 1994. The global impact of land-use change. *BioScience* 44:300-304.

Openshaw, S. 1984. The modifiable areal unit problem. Concepts and Techniques in Modern Geography 38, Norwich: GeoBooks.

Peters, D.P.C., J.R. Gosz, W.T. Pockman, E.E. Small, R.R. Parmenter, S. Collins, and E. Muldavin. 2006. Integrating patch and boundary dynamics to understand and predict biotic transitions at multiple scales. *Landscape Ecology* 21:19-33.

Phillips, S.J., R.P. Anderson, and R.E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modeling* 190:231-259.

Reuter, D.J., J. Walker, R.W. Fitzpatrick, G.D. Schwenke, and P.G. O'Callaghan. 2002. Using indicators to assess environmental condition and agricultural sustainability at farm to regional scales. Pp. 342-357, in McVicar, T., Rui, L., Walker, J., Fitzpatrick, R.W. and Changming, L. (eds.), Regional water and soil assessment for managing sustainable agriculture in China and Australia. ACIAR Monograph No. 84.

Reynolds, C.A., M. Yitayew, D.C. Slack, C.F. Hutchinson, A. Huete, and 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: 3487-3508.

Riitters, R.V. O'Neill, C.T. Hunsaker, J.D. Wickham, D.H.Yankee, S.P. Timmins, K.B. Jones, and B.L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. *Landscape Ecology* 10:23-29.

Riitters, K.H., R.V. O'Neill, and K.B. Jones. 1997. Assessing habitat suitability at multiple scales: a landscape-level approach. *Biological Conservation* 81:191-202.

Riitters, K.H., J.D. Wickham, J.E. Vogelmann, and K.B. Jones. 2000. Global patterns of forest fragmentation. Conservation Ecology 4(2):3 http//www.consecol.org.vol. 14/iss2/art3.

Riitters, K.H., J.D. Wickham, R.V. O'Neill, K.B. Jones, E.R. Smith, J.W. Coulston, T.G. Wade, and J.H. Smith. 2002. Fragmentation of Continental United States Forests. *Ecosystems* 5:815-822.

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.

Sanders, R., F. Shaw, H. MacKay, H. Galy, and M. Foote. 2006. National flood modeling for insurance purposes: using IFSAR for flood risk estimation in Europe. *Hydrology and Earth System Sciences* 9:449-456.

Schmidtlein, S., and J. Ewald. 2003. Landscape patterns of indicator plants for soil acidity in the Bavarian Alps. *Journal of Biogeography* 30:1493-1503.

Schumaker, N.H. 1998. A users guide to the PATCH model. EPA/600/R-98/135, U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Corvallis, OR.

Scott, J.M., F. David, B. Csuti, R. Noss, B. Butterfield, C. Groves, S. Anderson, S. Caicco, F. D'Erchia, T.C. Edwards, Jr., J. Ulliman, and G. Wright. 2003. Gap analysis: a geographic approach to protection of biological diversity. *Wildlife Monographs* 123.

Shippert, P. 2003. Why use hyperspectral imagery? *Photogrammetic Engineering and Remote Sensing*. 70:377-390.

Skoien, J.O., G. Bloschl, and A.W. Western. 2000. Characteristic space scales and timescales in hydrology. *Water Resources Research* (SWC):11-1 – 11-18.

Slonecker, E.T., D.B. Jennings, and D. Garofalo. 2001. Remote sensing of impervious surfaces: a review. *Remote Sensing Reviews* 20:1231-1242.

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

Smith, R.A., R.B. Alexander, and G.E. Schwarz. 2003. Natural background concentrations of nutrients in streams and rivers of the conterminous United States. *Environmental Science and Technology* 37: 3039-3047.

Sohl, T.L., A.L. Gallant, and T.R. Loveland. 2003. The characteristics and interpretability of land surface change and implications for project design. Photogrammetic Engineering and Remote Sensing. 70:439-450.

Stein, S.M., R.E. McRoberts, R.J. Alig, M.D. Nelson, D.M. Theobald, M. Eley, M. Dechter, and M. Carr. 2005. Forests on the edge: housing development on America's private forests. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-636.

Steinhardt, U., F. Herzog, A. Lausch, E. Muller, and S. Lehmann. 1999. The hermeroby index for landscape monitoring and evaluation. Pp. 237-254, in Pykh, Y.A., Hyatt, D.E., Lentz, RJ.M (eds.), Environmental Indices: Systems Analysis Approach, London: EOLSS Publishers Co. Ltd.

Stockwell, D., and D. Peters. 1999. The GARP modeling system: problems and solutions to automated spatial prediction. Int. J. *Geographic Information Science* 13, 143–158.

Streutker, D.R., and N.F. Glenn. 2006. LiDAR measure of sagebrush steppe vegetation heights. *Remote Sensing of Environment* 102:135-145.

Tenhunen, J.D., W. Mauser, and R. Lenz. 2001. Ecosystem science contributions and the implementation of an ecologically based landscape management in Central Europe. Pp. 621-636, in Tenhunen, J.D., Lenz, R., and Hantschel, R. (eds.), Ecosystem approaches to landscape management in central Europe. Ecological Studies 147, Springer.

Theobald, D.M., and N.T. Hobbs. 2002. A framework for evaluating land use planning alternatives: protecting biodiversity on private land. Conservation Ecology 6(1):5. http://www.consecol.org/vol6/iss1/art5/.

Theobald, D.M., and W.H. Romme. 2007. Expansion of the US wildland-urban interface. *Landscape and Urban Planning* (2007), in press.

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

Tuller, W., M.B. Araujo, and S. Lavorel. 2004. Do we need land-cover data to model species distributions in Europe. *Journal of Biogeography* 31:353-361.

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 erosion predictions. *International Journal of Geographical Information Science* 16:663-680.

Victorov, S. 1999. Environmental indices design with remotely sensed data. Pp. 287-294, in Pykh, Y.A., Hyatt, D.E., Lentz, RJ.M (eds.), Environmental Indices: Systems Analysis Approach, London: EOLSS Publishers Co. Ltd.

Victorov, S., I. Bychkova, T. Popova, and L. Sukhacheva. 2004. Remote sensing change detection in coastal zone landscapes: case study of St. Petersburg Region. Ecosys Suppl. Bd. 42:29-34.

Vina, A., A.J. Peters, and L. Ji. 2003. Use of multispectral IKONOS imagery for discriminating between conventional and conservation agricultural tillage practices. *Photogrammetic Engineering and Remote Sensing*. 69:537-544.

Vogelmann, J.E. 1995. Assessment of forest fragmentation in southern New England using remote sensing and geographic information systems technology. *Conservation Biology* 9:439-449.

Vogt, P., K.H. Riitters, M. Iwanowski, C. Estreguil, J. Kozak, and P. Soille. 2007a. Mapping landscape corridors. *Ecological Indicators* 7:481-488.

Vogt. P., K.H. Riitters, C. Estreguil, J. Kozak, T.G. Wade, and J.D. Wickham. 2007b. Mapping spatial patterns with morphological image processing. *Landscape Ecology* 22:171-177.

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. New York: Springer-Verlag.

Wade, T.G., K.H. Riitters, J.D. Wickham, and K.B. Jones. 2003. Distribution and causes of global forest fragmentation. *Conservation Ecology* 7(2):7.

Walker, J., S. Veitch, T.D. Dowling, R. Braaten, L. Guppy, and N. Herron. 2002. Assessment of catchment condition: The intensive land use zone in Australia. CSIRO, Canberra. http://www.affa.gov.au/catcon/.

Wamelink, G.W.W., C.J.F. ter Braak, and H.F. van Dobben. 2003. Changes in large-scale patterns of plant biodiversity predicted from environmental economic scenarios. *Landscape Ecology* 18:513-527.

Wascher, D.M. (ed.). 2005. European landscape character areas – topologies. Cartography and indicators for the Assessment of Sustainable Landscapes. Final Project Report for the European Union's Landscape Character Assessment Initiative (ELCAI). 5th Framework Programme on Energy, Environment and Sustainable Development (4.2.2), 150 pp.

Watts, R.D., R.W. Compton, J.H. McCammon, C.L. Rich, S.M. Wright, T. Owens, and D.S. Ouren. Roadless space of the conterminous United States. *Science* 316:736-738.

Wegehenkel, M., C. Prietzsch, and H. Jochheim. 2001. Spatially distributed simulation of evapotranspiration, soil water dynamics, and groundwater recharge in northeast German Agro-landscapes. Pp. 280-290, in Tenhunen, J.D., Lenz, R., and Hantschel, R. (eds.), Ecosystem approaches to landscape management in central Europe. Ecological Studies 147, Springer, The Netherlands.

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.

Wickham, J.D., D. Norton. 1994. Mapping and analyzing landscape pattern. *Landscape Ecology* 9: 7-23.

Wickham, J.D., K.B. Jones, K.H. Riitters, R.V. O'Neill, R.D. Tankersley, A.C. Neale, E.R. Smith, and D.J. Chaloud. 1999. Characterizing cumulative environmental impacts on mid-Atlantic watersheds. *Environmental Management* 24:553-560.

Wickham, J.D., K.H. Riitters, R.V. O'Neill, K.H. Reckhow, T.G. Wade, and K.B. Jones. 2000. Land cover as a framework for assessing risk of water pollution. *Journal American Water Resources*. 36:1417-1422.

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

Wickham, J.D., K.H. Riitters, T.G. Wade, M. Coan, and C. Homer. 2007. The effect of Appalachian mountaintop mining on interior forest. *Landscape Ecology* 22:179-187.

Wood, N., J. Good, and B. Goodwin. 2002. Community-based vulnerability assessment of a port and harbor to earthquake and tsunami hazards: Yaquina Bay, Oregon, *Natural Hazards Review* 3:148-157.

Young, S.S., and R. Harris. 2005. Changing patterns of global-scale vegetation photosynthesis, 1982-1999. *International Journal of Remote Sensing* 26:4537-4563.

Zhigal'skii, O.A., M.A. Magomedova, L.N. Dobrinskii, V.D. Bogdanov, V.G. Monakhov, and L.M. Morozova. 2003. A rationale for a regional network of ecological valuable areas. *Russian Journal of Ecology* 343:1-9.

Zurlini, G., L. Grossi, and O. Rossi. 1999. A landscape approach to biodiversity and biological health planning: the Map of Italian Nature. *Ecosystem Health* 5:296-311.

Zurlini, G., N. Zaccarelli, and I. Petrosillo.. 2004. Implementing an integrated framework for ecological risk assessment at the landscape scale. EcoSys Suppl. Bd. 42:4-15.