A Strategy for Estimating the Rates of Recent United States Land-Cover Changes


Abstract

Information on the rates of land-use and land-cover change is important in addressing issues ranging from the health of aquatic resources to climate change. Unfortunately, there is a paucity of information on land-use and land-cover change except at very local levels. We describe a strategy for estimating land-cover change across the conterminous United States over the past 30 years. Change rates are estimated for 84 ecoregions using a sampling procedure and five dates of Landsat imagery. We have applied this methodology to six eastern U.S. ecoregions. Results show very high rates of change in the Plains ecoregions, high to moderate rates in the Piedmont ecoregions, and moderate to low rates in the Appalachian ecoregions. This indicates that ecoregions are appropriate strata for capturing unique patterns of land-cover change. The results of the study are being applied as we undertake the mapping of the rest of the conterminous United States.

Introduction

Land-use and land-cover changes occur at all scales, and changes at local scales can have dramatic, cumulative impacts at broader scales. Consequently, land-use and land-cover changes are of concern at national and global levels because of impacts on land management practices, economic health, and social processes (Ojima et al., 1994). The challenge facing policy makers and scientists is that there is generally a lack of comprehensive data on the types and rates of land-use and land-cover changes, and even less systematic evidence on the causes and consequences of the changes. Lack of local, regional, and national data of sufficient reliability and temporal and geographical detail frustrates attempts at multiscale assessments of the implications of change.

Federal resource inventory programs, such as the U.S. Forest Service (USFS) Forest Inventory and Analysis (Gillespie, 1999) and the Natural Resources Conservation Service (NRCS) Natural Resources Inventory (NRCS, 2000) provide valuable statistical information. However, there is also a need for spatially explicit, thematically comprehensive data. Ideally, we need a program to develop periodic, wall-to-wall maps of land-cover change for the United States at a temporal interval appropriate for determining types, distributions, rates, agents, and consequences of change, but such a program would be cost prohibitive. A more feasible and cost-effective strategy is to use a sampling approach that incorporates a temporal, spatial, and informational resolution appropriate for regional and national evaluations (Dobson and Bright, 1994).

Recognizing both the need and challenges for providing data on both the statistical and spatial characteristics of contemporary change, we have designed a research strategy for documenting United States land-cover change. Our goal is to document the rates, causes, and consequences of 1973 through 2000 land-cover change within 84 ecoregions spanning the conterminous U.S. To achieve this goal, our research objectives are as follows:

- Develop a comprehensive methodology using sampling and change analysis techniques and Landsat multispectral scanner (MSS) and thematic mapper (TM) data for estimating regional land-cover change across the United States,
- Document the regional driving forces and consequences of change, and
- Prepare a national synthesis of land-cover change.

To date, we have completed six eastern U.S. ecoregions (Plate 1). In this paper, we present our methodology and a review of the early results.

A central premise of the project strategy is the use of a geographic framework for providing regional land-cover change estimates. Geographers have long used regional frameworks because they capture the essence and potential of the landscape, without masking the roles of environmental, social, and economic forces (Turner and Meyer, 1991). Pielies and Honea (unpublished paper, 1992) argue that ecoregions are the appropriate geographic framework for the study of environmental change. In fact, Turner et al. (1994) suggest that a strategy for looking at large area change and corresponding driving forces is by investigating “regional situations” where the distinctive patterns of physical, human, and social conditions are formed.

Background

Specifications for Land-Cover Change Data

Perhaps the clearest call for research on land-use and land-cover dynamics resulted from the National Research Council (NRC) response to a National Science Foundation (NSF) request to identify the “Grand Challenges in Environmental Sciences” (NRC, 2001). An interdisciplinary committee was asked to...
determine the most important research challenges over the next 20 to 30 years within the context of environmental problems. One of eight grand challenges is Land-Use Dynamics, which calls for the development of a comprehensive understanding of changes in land use and land cover that are critical to biogeochemical cycling, ecosystem functioning and services, and human welfare. The report concluded that "...improved information on and understanding of land use and land cover dynamics are essential for society to respond effectively to environmental changes and to manage human impacts on environmental systems" (NRC, 2001).

Two additional NRC reports emphasized the importance of land-use and land-cover change research. A 1999 report on Measures of Environmental Performance and Ecosystem Condition called for investigations of the complex relationships between humans and the environment and emphasized data collection and monitoring of both ecosystem processes and land-use and land-cover change (NRC, 1999). An NRC report titled Ecological Indicators for the Nation declared that the largest ecological changes caused by humans result from land use (NRC, 2000). Because these changes affect the ability of ecosystems to provide the goods and services that society depends on, an assessment of land-cover change is needed to understand the status of the Nation's biological resources.

Current Approaches for Estimating Change

While a great deal has been written regarding change-detection techniques using remotely sensed data, very little guidance exists for addressing large-area change detection (Dobson and Bright, 1994). Large-area change detection has generally relied on low-resolution sensors, such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), to provide information on general changes in vegetation indices or similar measures (Tucker et al., 1986; Hellden and Eklandh, 1988; Lambin and Strahler, 1994). The spatial resolution of such sensors, however, makes it difficult to identify and quantify the types of fine-scale land-cover changes that are often associated with anthropogenic change. The use of high-resolution imagery, such as Landsat TM data, makes this task much more feasible. However, wall-to-wall change detection using moderate- to high-resolution imagery for large areas presents stiff challenges with respect to accuracy, time, processing loads, and budgets. Despite these obstacles, some studies of note have used this approach. Perhaps the most ambitious effort was the Humid Tropical Forest project, where Landsat imagery from the 1970s to the present were manually interpreted to identify patterns of deforestation across the humid tropics (Skole and Tucker, 1993). The NOAA Coastal Change Analysis Project (C-CAP) uses Landsat TM data and computer-assisted techniques to map land-cover change in the coastal zones of the United States (Dobson et al., 1995).

Characterizing Land-Cover Change Using Remote Sensing

Spectral data recorded by remote sensing instruments can provide information on land-cover conversions and on changes in condition, but it is generally not a consistent indicator of land-cover change. Land-cover transitions often have very small changes in spectral response and may not be readily identifiable. Interpretation of tone, texture, shape, size, and pattern can help to identify land-cover change, but these elements are disregarded in many change analysis studies. The most straightforward technique for detecting change is the comparison of land-cover classifications from two dates. The use of independently produced classifications has the advantage of compensating for varied atmospheric and phenological conditions between dates, or even the use of different sensors between dates, because each classification is independently produced and mapped to a common thematic reference. The method has been criticized, however, because it tends to compound any errors that may have occurred in the two initial classifications (Gordon, 1980; Stow et al., 1980; Singh, 1989). The procedure has been successfully used in various land-cover change investigations, including assessing deforestation (Massart et al., 1995), urbanization (Dimyati et al., 1996), sand dune changes (Kumar et al., 1993), and the conversion of semi-natural vegetation to agricultural grassland (Wilcock and Cooper, 1993).

Simultaneous analysis techniques, including image differencing, ratioing, principal components analysis (PCA), and change vector analysis, are common change analysis approaches. Image differencing, i.e., subtraction between georegistered images (raw or transformed) from two dates, is probably the most widely used approach (Weisnigier et al., 1977, Vogelmann, 1988). Image ratioing (Howarth and Wickwire, 1981) and PCA (Bryne et al., 1980; Ribbed and Lopez, 1985) have also been widely used. Sohl (1990) successfully used change vector analysis to document land-cover change in the United Arab Emirates. Although often effective at identifying areas of spectral change, these techniques typically result in the creation of a simple, binary change mask.

Analytical Strategy

The analytical strategy we designed to assess the rates and characteristics of U.S. land-cover change is based on the following assumptions or requirements:

- The estimates of the rates of change should be as localized as possible.
- The temporal intervals should capture the major land-cover transformations taking place in each area.
- Spatial and statistical land-cover change data should include both what the land cover was at a given time and what it became at a later date.
- The land-cover data must be accurate and consistent, and
- The technical strategy used in this project must be extensible to provide continental and global coverage.
The approach used is to estimate change on an ecoregion-by-ecoregion basis using a probability sample of blocks randomly selected within each ecoregion. For each block, five dates of Landsat imagery are used to interpret and map land cover. The sample-block interpretations are compared to determine changes between periods. Then the sample results for each period within the ecoregion are analyzed to produce change estimates for the entire ecoregion. This provides us with the basis to understand land-cover change rates within and between ecoregions. Our goal is to detect ≥1 percent of the total change within each ecoregion at an 85 percent confidence level.

Generally, interpretation focuses on one ecoregion at a time so that analysts are immersed in the ecoregion’s unique issues and landscape characteristics. We are also investigating and documenting the primary driving forces of change affecting each ecoregion. However, the discussion of driving forces is beyond the scope of this paper.

**Temporal Framework: Satellite Data**

To reduce expenses, we used existing geoprocessed Landsat datasets as the primary source of data. Four of the five dates of Landsat MSS, TM, and enhanced thematic mapper plus (ETM+) data were available in a geocoded format as a result of processing done for two previous projects. The North American Landscape Characterization (NALC) project produced 1973, 1986, and 1992 geocoded Landsat MSS datasets for the conterminous United States and Mexico (Sohl and Dwyer, 1996). The 1992 and 2000 TM and ETM+ data, respectively, are from the Multiresolution Landscape Characterization (MRLC) initiative (Loveland and Shaw, 1996). New 1980 Landsat MSS acquisitions were obtained so that the temporal interval of 6 to 8 years could be maintained. Existing or planned geoprocessed multispectral data accounts for 80 to 90 percent of the required imagery (Table 1).

**Spatial Framework: Ecoregions**

The estimates of rates, driving forces, and consequences of land-cover change are being developed for 84 ecoregions originally defined by Omernik (1987) and later modified by the U.S. Environmental Protection Agency (EPA, 1999). Ecoregions (1) provide a means to localize estimates of the rates and driving forces of change, (2) play a significant role in determining the range of current land-use and land-cover types, and the trajectories of land use and land cover that may take place in the future, and (3) provide a framework that can be extended globally. Because Omernik’s (1987) ecoregion framework was developed by synthesizing information on climate, geology, physiography, soils, vegetation, hydrology, and human factors, the regions reflect patterns of land cover and use potential that correlate with patterns visible in remotely sensed data. The factors incorporated within the ecoregion framework strengthen its correspondence with patterns of land cover, disturbance types and frequencies, environmental issues of concern, and management practices and consequences. As we pursue this assessment of national land-cover change that occurred over the past three decades, we will be able to document the extent to which the ecoregion framework does or does not reflect trends, causes, and consequences of land-use patterns.

**Sampling Strategy and Design**

The probability sampling design used in this project is a stratified random sample of 20-ka by 20-km spatial units. The 60-m pixels within each sampled 20-km block constituted the sample. The initial decision to use a 20-km sampling unit represented a compromise between the conflicting objectives of estimating change in land-cover area and type and estimating change in landscape pattern. A smaller area sample unit would favor statistical efficiency for estimating change in area and type, whereas a larger unit would be desirable for characterizing landscape pattern.

To implement the sampling design, we overlaid the target universe (the conterminous United States) with a fixed grid of 20-km blocks. Although this partition was not randomly positioned, the sample units selected were determined by a randomized probability sampling protocol. The universe was next stratified geographically, with all 20-km blocks assigned to the ecoregion found at the block centroid. Stratum boundaries were thus aligned with boundaries created by the 20-km block partitioning and consequently do not correspond precisely with the irregular ecoregion boundaries. Defining strata in this manner maintained greater consistency in the size of the sampling units. Conversely, forcing the strata to adhere strictly to ecoregion boundaries would create sliver and other small-area sampling units at ecoregion borders.

Within each stratum, a simple random sample of 20-km sample blocks was selected. Each block within a stratum had an equal probability of being included in the sample, but, because strata were sampled with different intensity, 20-km blocks in different strata have different inclusion probabilities. The initial sample size chosen for each stratum was determined by standard sample size planning formulas (Cochran, 1977). The objective was to estimate the percentage of gross change with a margin of error of ±1 percent for an 85 percent confidence interval. An estimate of the variability of gross change among 20-km blocks within an ecoregion was derived from C-CAP data (Dobson et al., 1995). This estimate, which was applied to all ecoregions, affects only sample-size planning, and the option exists to supplement the sample size within a stratum if actual variability proves higher. The initial stratum sample sizes ranged from nine to eleven blocks, depending on the size of the ecoregion. Under these planning assumptions, the design would result in approximately the same relative precision for estimating gross change in each ecoregion. In reality, variability will differ within and among ecoregions, and all ecoregions will not have equally precise estimates of change.

Because the design is a probability sampling design, the data are categorically “representative” of the population (Kish, 1987). Although ecoregions are used to guide stratification and serve as the fundamental reporting unit, the analysis is not dependent on within-ecoregion homogeneity. Sampling theory ensures that the sampling-based estimates of change are unbiased or have very small bias. Thus, if land-cover change is highly heterogeneous within an ecoregion, large standard errors, but not bias, will result.

**Land-Cover Classification Scheme**

The primary derived data needed are general land-cover classifications of each sample block for each of the five dates. Because environmental issues are commonly associated with land changing from one general type to another, our mapping legend consists of the following 11 general land-cover types, with most based on the U.S. Geological Survey (USGS) Anderson system (Anderson et al., 1976):

- Developed (Urban and Built-up)
- Agriculture (Cropland and Pasture)
- Forest
- Mixed Forest
- Wetlands
- Tundra
- Water
- Barren
- Bared
- Seashore
- Ice

**Table 1. Characteristics of Landsat Datasets Used in the Analysis of Conterminous U.S. Rates of Change**

<table>
<thead>
<tr>
<th>Date</th>
<th>Landsat Sensor</th>
<th>Source</th>
<th>Processed Resolution</th>
<th>Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>MSS</td>
<td>NALC</td>
<td>60m</td>
<td>UTM</td>
</tr>
<tr>
<td>1980</td>
<td>MSS</td>
<td>New Acquisitions</td>
<td>60m</td>
<td>UTM</td>
</tr>
<tr>
<td>1986</td>
<td>MSS</td>
<td>NALC</td>
<td>60m</td>
<td>UTM</td>
</tr>
<tr>
<td>1992</td>
<td>MSS, TM</td>
<td>NALC, MRLC</td>
<td>60m, 30m</td>
<td>UTM, Albers</td>
</tr>
<tr>
<td>2000</td>
<td>ETM+</td>
<td>MRLC</td>
<td>30m</td>
<td>Albers</td>
</tr>
</tbody>
</table>
There were two primary factors affecting the design of our mapping legend. The first issue involved choosing the land-cover changes of interest. We are interested in land-use change, with cover serving as the surrogate for land use. This led to the use of the Anderson level 1 classes, because they were designed as use surrogates. However, we selectively modified the Anderson system by adding disturbed categories and separating mechanical (human-induced changes) and nonmechanical disturbances (typically natural change). Second, the use of moderate-resolution imagery (Landsat TM and MSS) meant that it was necessary to keep the land-cover interpretation at a general level to improve interpretation accuracy and consistency. This was especially necessary when interpreting Landsat MSS. It is important to recognize that our ability to identify and map land cover is limited by the technical specifications of Landsat MSS, TM, and ETM+ sensors, and by the local and regional landscape characteristics that affect the form and contrast of land-cover characteristics. Thus, consistent and accurate detection of fine-scale patterns and features will sometimes be difficult.

**Measuring Land-Cover Change: Data Preparation**

The Landsat MSS, TM, and ETM+ scenes had previously been georeferenced to root-mean-square errors of 1 pixel or less, but to differing projections. For the change analysis, all scenes were translated to a common Albers equal-area map projection. The majority of the NLCD MSS data were terrain corrected. However, approximately one-third of NLCD path/rows were processed prior to the implementation of terrain-correction techniques. It is not anticipated that this will cause any major problem, because these early NLCD scenes are primarily located in areas with negligible terrain variability.

Aerial photographs were also acquired for each sample block to provide higher resolution reference data. The National Aerial Photography Program (NAPP) generally provided one or two dates of color-infrared (CIR) and/or black-and-white photographs from 1980 to 1986. The National High Altitude Photograph (NHAP) Program generally provided one date of CIR and/or black-and-white photographs from 1980 to 1986. Generally, there was no suitable coverage for the early 1970s dates.

**Change Analysis Approach**

Traditional automated to semiautomated change analysis techniques are often based on spectral change information alone to identify land-cover change. Land-cover transitions may, however, be characterized by very small changes in spectral response and spatial extent. Texture, shape, size, and patterns are key components that can help to identify land-cover change, but these are components that have not often been used in automated change analysis studies. A skilled analyst making visual interpretations of imagery, however, can incorporate all these factors in making decisions on land cover and land cover change. For this study, land-cover maps for each date were created using manual, onscreen interpretation of Landsat data and using any available aerial photography as interpretation aids.

Sample-block processing began with the 1992 National Land Cover Database (NLCD) data (Vogelmann et al., 2001). This 30-m resolution database, with detailed classes aggregated to match the general land-cover legend described previously, served as the land-cover baseline. NLCD data were first manually edited using onscreen interpretation methods and using 1992 Landsat TM data with the NAPP aerial photographs serving as interpretation aids. This cleanup procedure was done because NLCD data were created at a different scale (multistate blocks) and were not meant for use in local-scale assessments.

Land cover for the 1973, 1980, 1986, and 2000 periods was then “back or forward classified” using 1992 land-cover data as the template. The analyst searched through, for example, the 1986 land-cover product, examining the Landsat images and aerial photographs for any valid land-cover changes that occurred between 1986 and 1992. Any identified change in land cover was manually digitized on-screen, and the resultant edits were incorporated to produce a 1986 land-cover product. After the 1986 land-cover interpretation was completed, the same procedures were used to create the 1980, 1973, and 2000 land-cover products.

The minimum spatial resolution of the Trends database is 60 m². Features with ground footprints less than 60 m² are not mapped. This means that high contrast features such as roads, which may have a distinct spectral signature but have ground dimensions of less than 60 m, are not mapped.

We recognize that postclassification comparison has been criticized because it compounds errors found in the two classifications. We believe four factors enable us to obtain highly accurate change information from the individual classifications:

- We rely on manual interpretations to derive change information instead of on automated approaches. Automated approaches cannot consistently achieve the local accuracy that can be obtained using manual interpretation.
- A primary difficulty is to achieve interpretations so consistent, temporally and spatially, that the Boolean differences represent real change with a minimum of commission errors (Dobson and Bright, 1994). When back and forward classifying, we begin with an exact copy of the temporally adjacent, finished landcover product. Areas that are identified as a changed were manually interpreted and recorded by a human analyst, minimizing commission errors.
- Mapping accuracy is tied directly to mapping area. We believe that the relatively small size of the individual sample blocks allows accurate land-cover mapping.
- Stratifying by ecoregion, coupled with the relatively small sample area, results in less land-cover heterogeneity. This should improve our ability to identify the range of spectral and spatial representations of land cover.

From the sample block interpretations, we analyze the temporal series of samples within each ecoregion to determine (1) the predominant types of land-cover conversions occurring within each ecoregion, (2) the estimated rates of change for these conversions, and (3) whether the types and rates of change are constant or variable across time. We also look for spatial correlations between conversion types and selected environmental factors, such as terrain characteristics, proximity to urban development, economic conditions, etc., in order to improve our understanding of potential drivers of change that can be used to develop future land-cover change scenarios.

**Validation**

It is extremely difficult to implement a consistent, comprehensive, quantitative accuracy assessment for such a large-area change database. One of the primary difficulties with the accuracy assessment of change products is acquiring an adequate database of historical reference materials. Contemporaneous (same year, same season) larger scale aerial or space photographs are the preferred sources of historical reference information, but it is improbable that such material will be available.

We recognize the importance of providing accuracy information, however, and efforts are underway to provide this information. The first step is to conduct a focused, formal accu-
racy assessment for a limited number of ecoregions, a process that is underway for the Northern Piedmont ecoregion (Plate 1). The Northern Piedmont was selected due to the availability of aerial photographs dating back to the early 1970s. The assessment entails the creation of a 1-km sub-grid that is nested within the 20-km sample blocks. These sub-blocks are stratified into categories of high, moderate, and low amounts of change. Twenty of the 1-km subblocks are randomly selected from each strata, and land-cover data are created using manual interpretation for each of the five dates. These data will then serve as a baseline for a formal accuracy assessment.

In addition to formal accuracy assessments, other forms of validation will be used when appropriate. We are field inspecting approximately 90 percent of the sample blocks, and collecting georeferenced ground photography. This provides a basis for checking the 2000 interpretations.

A final method of ensuring product reliability is to establish and follow strict methodological protocols. Following established methodologies and data quality standards provides assurance that the resultant products are accurate, although that accuracy is not quantified by some comparison to “truth.” Variability among multiple interpreters is a concern in a project such as this. To facilitate consistency, project interpreters periodically gather in an interactive setting to review each other’s work. Every interpreter presents each completed sample block to the full team. Every sample block is thoroughly examined by the team, content and methodologies are discussed, problems are identified, and changes are made, if needed.

Results
The application of this methodology to six eastern U.S. ecoregions resulted in a range of statistical and geographic summaries of land-cover change. The basis for conclusions regarding the characteristics of change ultimately comes from the Landsat-based land-cover interpretations, field observations, and socioeconomic ecoregion perspectives provided by county socioeconomic statistics. However, the Landsat interpretation provides the key measurements from which rates of change can be derived.

The actual change statistics can be considered relevant at three levels: (1) total enumerations of change for the individual 20-km by 20-km sample blocks, (2) change estimates for the ecoregion, or (3) change estimates for aggregations of ecoregions or other spatial entities (i.e., states). At each of these levels, at least three sets of land-cover change statistics are produced: (1) statistical summaries of land-cover types over time, (2) spatial extent of change over time, and (3) the land-cover transformations occurring over time. For example, the five land-cover interpretations for sample block 65-451 in central Georgia show a landscape that is predominantly forest but with substantial agricultural land and wetlands (Plate 2). Individually, the sample block serves as a local case study, providing data on the changes occurring within the sample block. In this example, the total change map in Plate 2 shows those areas that changed from one land-cover type one or more times between 1973 and 2000. An inspection of the 1973 to 2000 land-cover statistics for this block shows that forest cover decreased steadily from 1973 to 1986 but then expanded to its highest level by 2000 (Table 2). Mechanical disturbed cover, representing forest clear cuts in this area, increased each period. Agriculture followed the opposite trend, with increasing area until 1986, then steady decreases through 2000. Perhaps a clearer story of the magnitude of change is illustrated in the final panel of Plate 2 in which 22 percent of the land area has changed between 1973 and 2000. The measurement of this “footprint” of change varies from a low of approximately 4 percent (1973 to 1980) to a high of thirteen percent (1980 to 1992).

A more complete story of Southeastern Plains change comes from the analysis and aggregation of all eleven 20-km by 20-km sample blocks (Table 3). The Southeastern Plains summary statistics suggest little change in forests and modest decreases in agriculture and slight increases in mechanically disturbed land cover. The landscape transformations taking place within the ecoregion can be gleaned from change matrices generated from the land-cover interpretations covering 11 sample blocks and five time periods (Table 4). For this ecoregion, the two primary changes are the harvesting of forests and the replanting and regeneration of forests. These conversions are consistent with the active management associated with plantation forestry. The third most significant change, conversion of agricultural land to forests, could also be part of a regional transition to industrial forestry - but it may also correspond to cropland abandonment.

Table 5 displays the periodic and overall rates of change for all six ecoregions, including the calculated margin of error for

| TABLE 2. LAND-COVER CHANGE STATISTICS (PERCENTAGE OF COVER) FOR SOUTHEASTERN PLAINS SAMPLE BLOCK 65-451 |
|-----------|------|------|------|------|------|
| Water     | 0.8  | 0.8  | 0.8  | 0.9  | 0.9  |
| Developed | 0.7  | 0.7  | 0.7  | 0.7  | 0.7  |
| Mechanical Disturbed | 3.1 | 2.2 | 3.7 | 1.5 | 4.4 |
| Mining    | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| Forest    | 46.1 | 42.8 | 40.0 | 47.0 | 47.4 |
| Grassland/Shrubs | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| Agriculture | 37.6 | 39.3 | 40.2 | 34.3 | 32.5 |
| Wetland   | 13.7 | 14.2 | 14.6 | 15.5 | 14.0 |

| TABLE 3. LAND-COVER CHANGE STATISTICS (PERCENTAGE OF COVER) FOR THE SOUTHEASTERN PLAINS |
|-----------|------|------|------|------|------|
| Water     | 1.0  | 1.0  | 1.1  | 1.0  | 1.1  |
| Developed | 8.4  | 8.6  | 8.9  | 9.1  | 9.8  |
| Mechanical Disturbed | 2.2 | 2.4 | 2.9 | 3.8 | 4.8 |
| Mining    | 0.1  | 0.1  | 0.1  | 0.1  | 0.1  |
| Forest    | 53.4 | 52.5 | 52.0 | 52.7 | 52.5 |
| Grassland/Shrubs | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| Agriculture | 24.6 | 25.2 | 24.0 | 22.9 | 21.7 |
| Wetland   | 10.2 | 10.3 | 10.3 | 10.3 | 10.0 |

<p>| TABLE 4. LAND-COVER CONVERSIONS TAKING PLACE IN THE SOUTHEASTERN PLAINS |</p>
<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>1973 to 1980</th>
<th>Area (km²)</th>
<th>1980 to 1986</th>
<th>Area (km²)</th>
<th>1986 to 1992</th>
<th>Area (km²)</th>
<th>1992 to 2000</th>
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</thead>
<tbody>
<tr>
<td>6,644</td>
<td>Forest to Mechanical Disturbed</td>
<td>8,230</td>
<td>Forest to Mechanical Disturbed</td>
<td>11,409</td>
<td>Forest to Mechanical Disturbed</td>
<td>13,814</td>
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<tr>
<td>5,807</td>
<td>Mechanical Disturbed to Forest</td>
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<td>Mechanical Disturbed to Forest</td>
<td>8,626</td>
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<td>10,692</td>
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</tr>
<tr>
<td>2,187</td>
<td>Forest to Agriculture</td>
<td>2,224</td>
<td>Agriculture to Forest</td>
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<td>Agriculture to Forest</td>
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<tr>
<td>7,14</td>
<td>Agriculture to Forest</td>
<td>1,591</td>
<td>Forest to Agriculture</td>
<td>770</td>
<td>Forest to Agriculture</td>
<td>1,547</td>
<td>Forest to Urban</td>
</tr>
</tbody>
</table>
Plate 2. Land-cover interpretations for Southeastern Plains, sample 65-451. Each sample is 20 km in height and width.

Plate 3. Land-cover change in sample 62-4 associated with tornado activity and deforestation, with subsequent reforestation. Each sample is 20 km in height and width.

an 85 percent confidence interval for each change period. There are several points associated with the statistics in this table:

- Strictly from a geographic perspective, there is a trend of high rates of change in the Plains ecoregions, moderate to high rates in the two Piedmont ecoregions, and moderate to low rates of change in the Appalachian ecoregions.
- The period of greatest change was the 1992 to 2000 period. While this may be logical because the last decade of the century was a period of unprecedented economic growth, there may be other explanations (see the Discussion section).
- Our goal is to detect change with a 1 percent margin of error, but we were only successful for 11 of the 24 reporting periods (Table 5). In those cases, a higher margin of error was often coincident with a very high rate of land-cover change (i.e., Southeastern Plains, Mid-Atlantic Coastal Plains, and Piedmont). Furthermore, a single unusual event affecting one sample block can cause precision limits to be exceeded. Note the 1980 to 1986 period in the North Central Appalachians ecoregion. During this period, a series of tornados touched down in a western part of the ecoregion, causing substantial deforestation (classified as nonmechanical disturbed) and unusually high overall change (Plate 3).

Table 6 lists the primary land-cover transformations of each ecoregion. The key lessons taken from this table include the following:

- The Plains ecoregions (Southeastern Plains and Mid-Atlantic Coastal Plains) are experiencing significant forest harvesting. In both cases, the second most common transformation is the reforestation of the disturbed lands, signifying the rapid harvest-

<table>
<thead>
<tr>
<th>Table 5. Overall Rates of Change for the Six Eastern Ecoregions</th>
</tr>
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<tbody>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Mid-Atlantic Coastal Plains</td>
</tr>
<tr>
<td>Southeastern Plains</td>
</tr>
<tr>
<td>Northern Piedmont</td>
</tr>
<tr>
<td>Piedmont</td>
</tr>
<tr>
<td>Blue Ridge Mountains</td>
</tr>
<tr>
<td>North Central Appalachians</td>
</tr>
<tr>
<td>Overall</td>
</tr>
</tbody>
</table>

Collectively, these results show clear differences in the types and rates of land-cover conversions between ecoregions. The salient characteristics of land-cover change in each ecoregion are:

- **Mid-Atlantic Coastal Plains**: The region is undergoing significant change, with decreasing forest cover, even when regeneration rates are considered. Increasing developed lands occurred during the entire observation period.

- **Southeastern Plains**: This area is experiencing the highest rates of change, with cyclic forest harvesting and regeneration being the dominant changes. There is also continuing back-and-forth conversion between agricultural lands and forests. A significant increase in developed lands occurred during the 1992 to 2000 period.

- **Piedmont**: While loss of forestland was the primary forest transformation, increases in developed lands were nearly as great.

- **Northern Piedmont**: The primary transformation was the steady increase in developed land cover, typically through the

as illustrated in Figure 1, the area is still losing forest cover, with only the Southeastern Plains increasing in forest land use (combination of the forest and mechanically disturbed classes).

- The primary conversion in the Northern Piedmont and the Blue Ridge consists of increasing developed (urban) lands. However, all ecoregions experienced an increase in developed lands, with the greatest overall amount of new urban land found in the Piedmont ecoregion (Figure 2).
Table 6. Primary Transformations for the Six Eastern Ecoregions

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>Area (km²)</th>
<th>1973 to 1980 Conversion</th>
<th>Area (km²)</th>
<th>1980 to 1986 Conversion</th>
<th>Area (km²)</th>
<th>1986 to 1992 Conversion</th>
<th>Area (km²)</th>
<th>1992 to 2000 Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Atlantic Coastal Plains</td>
<td>2,120</td>
<td>Forest to Mechanical</td>
<td>1,950</td>
<td>Forest to Mechanical</td>
<td>2,157</td>
<td>Forest to Mechanical</td>
<td>2,506</td>
<td>Forest to Mechanical</td>
</tr>
<tr>
<td>Southeastern Plains</td>
<td>6,600</td>
<td>Disturbed</td>
<td>8,091</td>
<td>Disturbed</td>
<td>11,226</td>
<td>Disturbed</td>
<td>13,542</td>
<td>Disturbed</td>
</tr>
<tr>
<td>Northern Piedmont</td>
<td>182</td>
<td>Agriculture to Urban</td>
<td>184</td>
<td>Agriculture to Urban</td>
<td>127</td>
<td>Agriculture to Urban</td>
<td>347</td>
<td>Agriculture to Urban</td>
</tr>
<tr>
<td>Blue Ridge Mountains</td>
<td>112</td>
<td>Forest to Urban</td>
<td>95</td>
<td>Forest to Urban</td>
<td>85</td>
<td>Forest to Urban</td>
<td>192</td>
<td>Forest to Urban</td>
</tr>
<tr>
<td>North Central Appalachians</td>
<td>208</td>
<td>Forest to Mechanical</td>
<td>266</td>
<td>Mechanical to Forest</td>
<td>296</td>
<td>Forest to Mechanical</td>
<td>274</td>
<td>Mechanical to Forest</td>
</tr>
</tbody>
</table>

Forest Cover vs. Forest Use Selected Eastern U.S. Ecoregions

Figure 1. Changing forest land cover and land use in the six eastern ecoregions.

Increase in Urban Land Cover 1973 - 2000

Figure 2. Increasing urban land cover in the six eastern ecoregions.

Discussion

Data quality and availability play a key role in determining product accuracy. Mapping the older time periods, specifically the 1973 date, was considerably more difficult than mapping the other time periods because of relatively coarse resolution (MSS instead of TM or ETM+), and lack of aerial photographs to use as interpretation aids. As a result, it is expected that land-cover maps for the 1973 date are of lower accuracy than the other dates. An extension of our methodology for future dates would be greatly aided by the use of Landsat ETM+ data rather than MSS data. The new NAPP acquisitions provide an excellent source of consistent aerial photographs. Digital aerial photographs, digital orthophoto quadrangles, or high-resolution space-platform photography or imagery would also enhance our ability to use photography as an interpretation aid.

Some land-cover types were more difficult to interpret than others. Wetlands mapping, for example, is extremely problematic. National Wetlands Inventory (NWI) data are recognized as the most authoritative and accurate source of wetlands land-cover data for the conterminous United States (Kiraly et al., 1990). When mapping wetlands, we used an approach similar to that of Dobson and Bright (1994), where the NWI category is considered correct for a given pixel area for each time period, unless spectral signatures or collateral data suggest that the NWI category is incorrect or a land-cover change has occurred.

Another difficulty was encountered with the "mechanical disturbed" class, a category largely populated by clear-cutting of forests for the ecoregions described in this paper. Clear-cut areas revegetated quickly in the eastern and southern ecoregions. Given our 6- to 7-year span between mapping dates, it is very easy to miss a clear-cut that occurs shortly after a mapping date because the area has revegetated by the next date. It is also conversion of agricultural land. The rates of urbanization were greatest in the 1992 to 2000 period. Overall, this region is experiencing modest change.

Blue Ridge Mountains. This region is experiencing little change. Conversion of forest to developed lands is the primary land transformation. The rate of urbanization for the 1992 to 2000 period was almost double that experienced during the earlier period.

North Central Appalachians. This area experienced only modest change. Most of the conversions were the cyclic harvesting and regeneration of forest. However, a small increase of mined lands occurred in several periods. The 1980 to 1986 period experienced significant forest loss because of the tornado described previously.

Mid-Atlantic Coastal Plains. This region was experiencing the greatest change. Conversion of agricultural land to developed lands was the primary land transformation. The rate of urbanization for the 1992 to 2000 period was almost double that experienced during the earlier periods.
difficult to define precisely the stage where a regenerating forest is no longer considered “disturbed” and can once again be labeled as “forest.”

We need to improve our understanding of the temporal trends represented in our rates-of-change data. Specifically, the consistently high rates of change for the 1992 to 2000 period require further investigation (see Table 5). Although it is possible that this period is indeed the period of maximum land-cover change, we cannot rule out two other explanations for the apparent rapid change. First, we are concerned that the high 1992 to 2000 change rates may be the result of improved interpretations because this was the only period in which Landsat TM data were available for both endpoints. Resolution limitations may reduce the detection of MSS to MSS change. Second, the 1992 to 2000 period has the widest time interval of all change periods, so perhaps the extra years are the reason for the largest amount of change. We are looking into all three explanations.

Through experimentation and practice, and based on our information requirements, we have found that manual interpretation provides high quality land-cover change results. This is especially the case when mapping complex local land-cover patterns. Because land-cover change is highly localized, it is critical that we be able to detect and map very small patches of change.

We also recognize that manual interpretation is labor intensive and lacks the efficiency of automated classification when mapping large areas. The level of effort can vary greatly, depending upon the complexity of ecoregion land cover. For example, interpretation of the very complex land-cover mosaic making up the Piedmont took an average of 120 hours per sample block, while the simpler North Central Appalachians and Blue Ridge Mountains averaged 40 hours per sample block. The Holy Grail of change detection is still total automation and high accuracy. However, methods that reduce labor costs while maintaining consistency and accuracy are needed.

The early evidence shows that ecoregions capture unique mosaics of current land cover, limit the trajectories of change that are occurring, and therefore provide a predictive framework for documenting and projecting future land-cover changes. We also think that the early results illustrate the need to focus on the spatial characteristics of change in addition to statistical summaries of change.

We think that the sampling approach is valid for providing land-cover change information. For approximately half of the epochs for the ecoregions discussed in this paper, we failed to reach our targeted goal of detecting overall land-cover change within ±1 percent at an 85 percent confidence interval. Based on data from the pilot ecoregions, it is apparent that decreasing the sample block size to 10 km by 10 km and doubling or tripling the number of sample blocks would result in substantially improved precision, and yet require no more processing time. This design change would not result in a substantial increase in Landsat purchasing and processing. In addition, we are also evaluating stratification by anticipated high-change and low-change blocks within each ecoregion to improve precision estimates.

Plans

Our goal is to contribute to an improved understanding of the spatial and temporal dimension of land-use and land-cover change. The analysis of the six eastern U.S. ecoregions provided valuable evidence of the types of land-cover trends data that can be collected using a simple sampling design and historical Landsat data. Using our early results and the lessons learned to date, we are improving our design on the basis of issues raised in the Discussion section. Over the next several years, we intend to apply the strategy presented in this paper to document the rates of change for all 84 conterminous U.S. ecoregions.

Our next steps are fourfold. First, we will embark on the analysis of all 84 ecoregions. Second, we will begin linking the remote sensing measurements of change with socioeconomic data and extensive field observations to document the major driving forces of change. Third, we will further explore the spatial characteristics of change by investigating the changes in landscape patterns, as represented by the spatial configurations of land cover over time found in the sample blocks. Fourth, this will provide several dimensions of change information that will permit a national synthesis of contemporary change. This synthesis will include (1) a summary of the national rates of land-cover change, (2) the frequency of different land-cover conversions, (3) the identification of the most dynamic regions of the country, and (4) an assessment of which periods were most dynamic between 1970 and 2000.

Acknowledgments

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References


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