Kurt H. Riitters, James D. Wickham, James E. Vogelmann, and K. Bruce Jones. 2000. National land-cover pattern data. *Ecology* **81: 604.**

Introduction

Land cover and its spatial patterns are key ingredients in ecological studies that consider large regions and the impacts of human activities. Because humanity is a principal driver of land-cover change over large regions (Turner et al. 1990), land-cover data provide direct measures of human activity, and both direct and indirect measures of ecological conditions within human-dominated landscapes (O'Neill et al. 1997). Thus, incorporating land-cover information is a way to place humans directly into regional ecological models and assessments.

Numerous studies have shown the importance of proportions of different land-cover types (e.g., forest, agriculture, urban) in explaining the spatial variation of other environmental parameters (e.g., Beaulac and Reckhow 1980, Soule et al. 1994, Schueler 1994, Hunsaker and Levine, 1995, Young et al. 1996). Other studies have shown that land-cover pattern is also important (Lynch and Whigham 1984, Krummel et al. 1987, Hunsaker and Levine 1995, Vogelmann 1995). Although patterns are sometimes easy to see on a land-cover map, further processing of land-cover data is needed to quantify those patterns. In other cases, further processing is needed to extract pattern information that is not visually apparent.

We are producing a set of land-cover pattern maps for the United States to help us to understand and assess the ecological implications of regional spatial patterns. The land-cover pattern data are suggested for several purposes, depending on the scale of inquiry. First, they may provide contextual information for studies involving a set of field sites, and could be used as independent variables or attributes for stratification. Second, they can be used as indicators in landscape-scale assessments of ecological conditions, and can be summarized by assessment units such as watersheds, ecoregions, or counties. Third, they may be useful as dependent variables in even coarser-scale biogeographic models, or in socio-economic models of human land use and development.

The derived data will be most useful in studies that require consistent and comparable land-cover pattern measurements over large regions. In principle, anyone with access to image processing systems could produce these maps of pattern indices for a particular need. The rationale for distributing a national set of maps is that there may be community benefit in a consistent national set. If there are many users of the national land-cover pattern maps, then it will be easier to integrate the consequences of human activity on land-cover pattern change from a number of otherwise disparate investigations. In most cases, the maps of pattern indices will be used in conjunction with the original land-cover maps and other data.

Methods

We use the land-cover maps from the Multi-Resolution Land Characteristics (MRLC) Consortium (Loveland and Shaw 1996). The MRLC Consortium is a federal initiative with a principal objective to collect and process Landsat Thematic Mapper (TM) data for the lower 48 states. As part of the MRLC Consortium activities, a land-cover data set is being developed for the conterminous United States at 30 m resolution. The primary source of data for this effort is 199 1- 1993 vintage TM data. Other sources of spatial data are being used, including elevation, population, soils, and available land-cover information derived by other programs (e.g., National Wetlands Inventory data, State land-cover data sets). In general, leaf-on and leaf-off TM mosaics are classified by using a combination of unsupervised and supervised classification methods, and the ancillary data are then used to resolve conflicts and to refine the classification (Vogelmann et al. 1998a,b). Twenty-three land-cover ! types approximating the Level II thematic detail of Anderson et al. (1976) are labeled (Table 1).

Table 1. The MRLC land-cover types that are the basis for the land-cover pattem indices described in this paper. Types are grouped by **major** category such as "water" and "developed."
Water

Open water
Perennial ice / snow
Developed
Low intensitv residential
High intensity residential
High intensity commercial / industrial / transnortation
Barren
Bare rock / sand / clay
Quarries / strip mines / gravel pits
Transitional
Natural forested upland
Deciduous forest
Evergreen forest
Mixed forest
Natural shrubland
Deciduous shrubland
Mixed shrubland
Evergreen shrubland
Non-natural woody
Planted / cultivated
Herbaceous upland natural / semi-natural
Grassland / herbaceous
Herbaceous planted / cultivated
Pasture / hay
Row crops
Small grains
Bare soil
Urban / recreational grasses
Wetlands
Woody
Emergent herbaceous

We apply a series of spatial filters to the land-cover maps, to derive new maps of pattern indicators. A convolution filter (e.g., Pratt 1978, Schowengerdt 1983, Gonzalez and Woods 1992) places a "window" (support region, or kernel) on each pixel of land cover, calculates the pattern index within the window, and puts the result on a new map at the same location. Thus, the value of a pixel in one of the new maps represents an index of land-cover pattern for the surrounding window in the original land-cover map. Six pattern indices are mapped: forest connectivity, forest area density, land-cover connectivity, land-cover diversity, the U-index (O'Neill et al. 1988), and landscape pattern types (Wickham and Norton 1994).

The pattern indices are calculated from the frequencies of land-cover types, and from the tendencies of a given land-cover type to be spatially autocorrelated (i.e., to appear in clumps as opposed to isolated pixels). Consider a window placed somewhere on a land-cover map. Let t be the number of land-cover types, after any aggregation of land-cover types that is particular to a given pattern index. Let P_i ($i = 1$ to t) be the proportion of non-missing pixels in the window of the z^{th} type. The P_i values are used in four of the six indices as follows.

Forest area density, an index of forest amount, is the proportion of forest in the window, as determined from a map with all forest types aggregated into one. The index is continuous over [0,1], and is available for three window sizes (9 x 9 pixels, 27 x 27 pixels, and 8 1 x 8 1 pixels; roughly equivalent to 7, 66, and 590 ha). The *U-index* (after O'Neill et al. 1988) is the proportion of agriculture plus developed land-cover types in the window, and it measures general land use pressure by humans. This index is also continuous over [0,1], and is available for a window size of 66 ha.

Landscape pattern types (LPT's; after Wickham and Norton 1994) provide geographic strata for identifying differences in landscape characteristics (e.g., forest patch size, amount of edge). They are motivated by the prevailing tendency for land cover to be spatially autocorrelated. The LPT's are evaluated within 590-ha windows, and 19 categorical values are identified based on the local proportions of aggregated forest, developed, and agriculture land-cover types. The proportions are compared to each other, and to the critical values of 0.1 and 0.6, to yield categories indicating general land use themes. Landscapes dominated by one land cover appear to be qualitatively different from landscapes with a more even distribution of land-cover types (Wickham and Norton 1994). As a practical matter, where $P_i > 0.6$ the i^{th} land-cover type appears as the "background" upon which other land-cover types are superimposed. Igno! ring relatively minor amounts (i.e., $P_i < 0.1$) of the i^{th} land-cover type helps to clarify regional patterns.

Land-cover diversity is analogous to Simpson's (1949) index; land-cover type proportions here replace the species proportions in the original equation, $1 - \Sigma_i P_i^2$. The index is continuous over [0,1] for 66-ha windows and higher values are taken to indicate greater diversity. While no single diversity measure can be definitive (e.g., Hurlbert 1971), at least one must be selected if we are to make a measurement of land-cover diversity. Simpson's index is easy to visualize and its properties are understood by many ecologists (e.g., Magurran 1988). Compared to most other diversity indices, Simpson's index is relatively more sensitive to changes in abundant land-cover types and less sensitive to changes in rare types (and thus, to classification errors in the land-cover maps).

The other two indices are texture measures derived from an attribute adjacency table (e.g., Musick and Grover 1991), in which F_{ij} (i,j = 1 to t) is the frequency of adjacent pixel pairs with land-cover types $\{i,j\}$. When forming the attribute adjacency table, adjacency is evaluated in the four cardinal directions, each edge is counted once, the order of pixels in pairs is not preserved, and pairs involving a missing pixel are not included (Riitters et al. 1996b). Define $G_i = \Sigma_j F_{ij}$ and $W_i = F_{ii} / \Sigma_{i,j} F_{ij}$ for the i^{th} land-cover type.

Forest connectivity was measured by the conditional probability that two adjacent pixels in a given window are forest, given that the first is forest. The index is calculated as F_{ii} / G_i where i refers to all forest types aggregated into one. It is continuous over [0, 1], and is derived for three window sizes (7, 66, 590 ha). The index is of interest because of concern regarding forest "fragmentation," which can be estimated as one minus the connectivity index.

Land-cover connectivity (Wickham and Riitters 1995) was measured as $\Sigma_i W_i$, i.e., as the overall probability that adjacent pixels had the same land-cover type. The index is continuous over [0,1] and is available for a 66-ha window size. It is similar to contagion (O'Neill et al. 1988, Li and Reynolds 1993), which measures the overall tendency for land cover to appear in non-random pairings. Larger connectivity values indicate relatively less overall fragmentation in the window.

For computer storage, the continuous indices (all except landscape pattern types) are converted to discrete values in the range [1,255], with zero reserved for missing values. All pixels labeled as water or missing in the land-cover map are labeled as missing in the derived maps. In addition, some other land-cover types are labeled as missing for some indices, and these locations will have missing values for those cases. For example, the "barren, transitional" land-cover type could represent either forest or agriculture when calculating the LPT index and was treated as a missing value.

The maps are distributed in a generic binary format that is suitable for use with most image processing and geographic information systems. The map projection is Albers conical equal area, with the same geographic references as the land-cover maps. The documentation complies with the Federal Geospatial Data Committee (FGDC) standard and provides additional procedural information.

Results

Fig. 1 illustrates some of the pattern indices in the Boston, Massachusetts metropolitan area. The land-cover legend has been condensed to seven categories for this illustration (Fig. la). The area is approximately 60 km on each side and contains approximately 4×10^6 pixels. Urban and forested land-cover types dominate the area, and a general land-use pattern of development along transportation corridors is visible.

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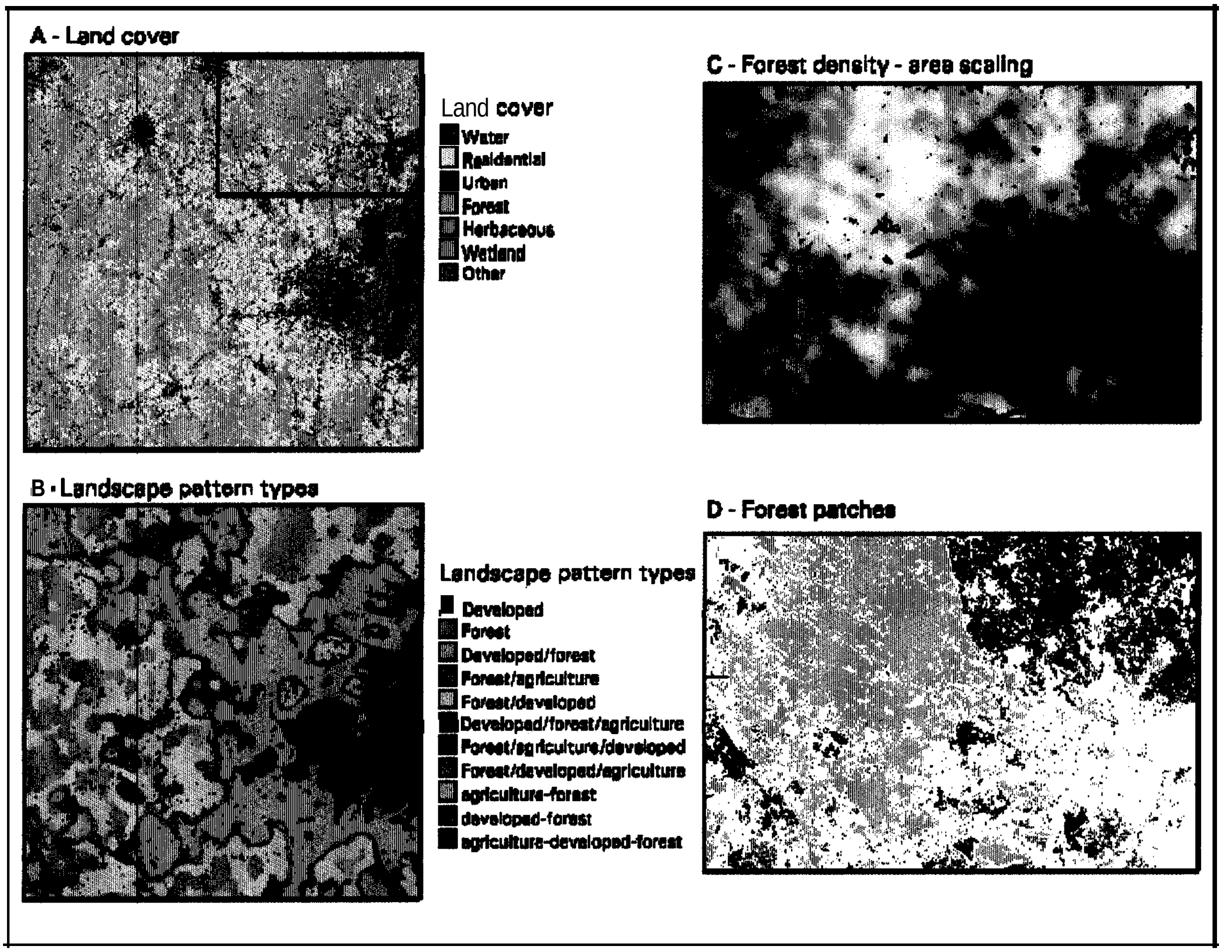


here because there is little agriculture. The most striking feature of this map is the apparent gradient from concentrations of urban land use to concentrations of forestland use. Along the gradient, the LPT map identifies regions of decreasing urban land use, with forest appearing within an urban background near centers of development, and urban appearing within a forest background nearer to the large forest tracts. The banded feature labeled 'developed-forest' indicates ecotones or regions of transition from mostly urban to mostly forest land-cover types.

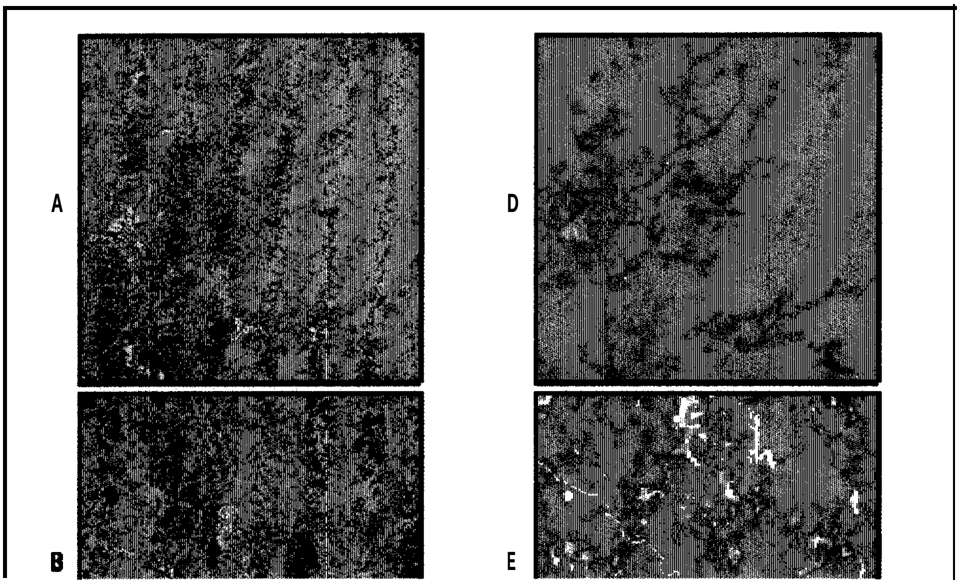
The smaller area in the box in the upper-right part of Fig. la illustrates some other land-cover patterns. This sub-region is approximately 20 km by 30 km and contains approximately 7x 10^5 pixels. In Fig. lc, the forest area density index at three window sizes is represented by the intensities of red (largest window), green, and blue (smallest window) used to render each pixel

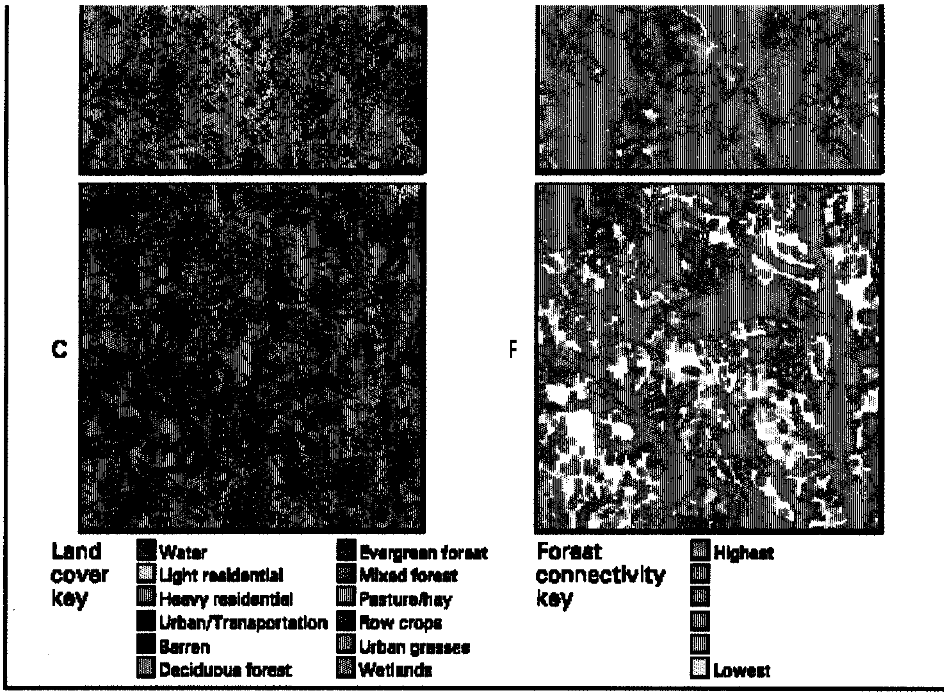
(Milne 1992). The resulting colors indicate where the index value changes with'scale (i.e., window size), and what the change is.

For example, consider a non-forested area within a large tract of forest. This area will appear red because the smaller windows (green or blue) contribute no colors, that is, the window must be very large to include forest. If the non-forested area is made somewhat smaller, then it will now appear yellow because the medium-size window (green) also contributes color, and red and green make yellow. White indicates areas that are completely forested, and black indicates areas lacking forest for the three window sizes. Shades of gray indicate areas with the same index value over the three window sizes; areas that are not gray are regions where forest area density is scale-dependent.

A forest patch map, which is not in our database but is routinely produced by a geographic information system, is shown for comparison in Fig. 1d. Random colors were used to render individual patches for the sub-region. There, the forest patch map has two large patches that are separated by a transportation corridor, and a very large number of smaller patches. Without more information, every pixel in a patch is essentially identical to every other pixel in that patch. But consider the large but highly-fragmented red patch from the point of view of a species that requires forest edge habitat; some parts of this large patch may provide much more edge habitat than other parts. By combining the data from Fig. lc and Fig. 1d, the amount and location of edges can further characterize forest patches.

Fig. 2 illustrates the relationship between land cover and the forest connectivity index (in 7-ha windows) for three different locations in the Southeastern United States. Each map covers





15 km^2 and contains 2.5 x 10^5 pixels. Forest land cover dominates the Appalachian location (Fig. 2a, north of Asheville, North Carolina) but is less abundant in the Piedmont (Fig. 2b, west of Laurens, South Carolina) and Coastal Plain (Fig. 2c, east of Cordele, Georgia) locations. In the Appalachian location, anthropogenic land-cover types along rivers dissect upland forests. The opposite pattern occurs in the Coastal Plain location where most of the forest land cover (including forested wetlands) is adjacent to rivers.

The corresponding maps of the forest connectivity index in 7-ha windows are shown in Fig. 2d (Appalachian), Fig. 2e (Piedmont), and Fig. 2f (Coastal Plain). The index ranges from low connectivity and high fragmentation (yellow) to high connectivity and low fragmentation (cyan). White represents windows for which there was no forest and hence no information about forest connectivity, or for which the land cover at the center of the window was water. These examples show that the same index value can be obtained in remarkably different landscapes if the local (i.e., within-window) patterns are similar.

The National Land-cover Pattern Data are available online for individual States at http://for3019pc2.cfr.ncsu.edu/index.html. Please note that the maps are quite large and require decompression and import into a GIS or image processing system for viewing.

Discussion

Despite the advent of Landsat imagery more than 25 years ago, there has not been a national effort to consistently map land cover across the United States. In the past, land-cover maps have been acquired to meet local objectives across a wide array of remote platforms. The MRLC Consortium has facilitated the development of a nationally consistent land-cover data set for conducting ecological assessments and for exploring links between ecological pattern and process at regional scales. Regional MRLC land-cover data and the derived pattern maps are currently available for the eastern half of the United States, and completion is expected by the end of 2000. The existence of consistent land-cover maps now makes it possible to derive consistent land-cover pattern maps in a way that was not previously possible (Mladenhoff et al. 1997).

Pattern maps are useful because they quantify biologically relevant information that is not necessarily evident from a land-cover map. Yet much remains to be learned about how to measure pattern in meaningful ways. It is important to test a central hypothesis of landscape ecology, that ecological patterns and processes are linked (e.g., Forman and Godron 1986, Turner 1989, Levin 1992). The pattern data provided here may encourage more such tests and in this way, the pattern information may become more reliable for characterizing ecological conditions over large regions.

Spatial scale is also important, not only because different ecological patterns emerge at different scales of investigation (Wiens 1989), but also because all measures of pattern are more or less sensitive to it, sometimes by design (Gustafson 1998). Any measurement necessarily fixes the scale, and inferences to other scales are tenuous without some justification (Allen et al. 1987).

Our choices of indices and scales are based on our experiences with similar land-cover maps in the context of a national monitoring program (EPA 1993, Riitters et al. 1995, 1996a,b, 1997, Jones et al. 1996, 1997, O'Neill et al. 1996, 1997, Cain et al. 1997, Wickham et al. 1997). We expect that the pattern data presented here will be useful for testing hypotheses related to water quality and wildlife habitat at regional scales. Our protocols are a starting point and do not exhaust the pattern information that could be obtained from the MRLC maps; Turner and Gardner (199 1) and Gustafson

(1998) describe other possibilities. Our future contributions will depend in part on lessons learned from this initial distribution.

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