Quantitative Analysis of Ecotones Using a Geographic Information System

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ABSTRACT: GIS techniques were developed and evaluated for analyzing ecotones, zones of transition between adjacent ecological systems. Raster-based GIS techniques were used with remotely sensed data to detect, classify, and measure ecotones. The ecotones of six general land cover classes were identified using a moving window GIS technique to scan a classified 324 km^2 Landsat thematic mapper image of north central Minnesota. Ecotone length was measured by boundary associations at the edges of land cover patches (e.g., water/lowland deciduous shrubs, coniferous trees/deciduous trees). Ecotones between areas of high and low vegetation biomass were analyzed using normalized difference vegetation index (NDVI) values calculated for the same thematic mapper scene. Biomass ecotones were located by scanning the image for areas of maximum NDVI contrast within a 3 by 3 pixel moving window. GIS anslysis of remotely sensed imagery provided ecotone detection and quantification capabilities which would have been more difficult to impossible without a GIS. This ecotone analysis provided new insights about the association of different cover types in the landscape.

INTRODUCTION

ECOLOGISTS HAVE LONG acknowledged the importance of ecotones, zones of transition between adjacent ecological systems. Ecotones were historically viewed as areas of exchange or competition between adjacent ecological communities (Clements, 1905). They commonly contain more species of organisms and higher population densities than either community flanking the ecotone (Odum, 1971). Wildlife managers have recognized that some types of ecotones support high diversity and abundance of vertebrates (Leopold, 1933; Dasmann, 1964), and have developed habitat management strategies to optimize the amount of "edge."

There has been a recent resurgence of interest in ecotones, however, with regard to their influence on biodiversity, their effect on the flux of materials and energy in the landscape, and their response to global climatic change (di Castri *et al.*, 1988). Human activities have increasingly altered the extent of ecotones throughout the world, and may have altered the mediating role of ecotones in maintaining ecological flows between ecosystems. Furthermore, ecotones may be useful indicators of ecological change due to global warming, because ecotones occur where plant species are at the extreme limits of tolerance for change.

Traditional ecotone mapping techniques, in which ecotones are subjectively located based on species occurrence records (e.g., Curtis, 1959), have limited applicability to the current concept of ecotones, for two reasons. First, ecotones are now defined more broadly (Holland, 1988) to include physical as well as biological transitions, transitions in ecological processes as well as transitions in organism distribution, and transitions at spatial scales ranging from local (e.g., edges of agricultural fields) to global (e.g., boundaries of major biomes). Second, the only information conveyed by an ecotone drawn as a line on a map is its location. New techniques are needed to characterize ecotones as entities in themselves, rather than merely boundary lines.

Remote sensing has potential for ecotone detection and has been used to track the location of the ecotone between desert and arable land in the Sahara (Tucker *et al.*, 1985) and the southwestern United States (Mohler *et al.*, 1986). However, remotely sensed images provide information about the entire landscape, not just the ecotones. Therefore, GIS techniques are needed to extract information about the ecotones from the image as a whole.

Textural analysis, which provides a numerical measure of image heterogenity based on spectral reflectance, has potential application to ecotones, which are by definition heterogenous. Nellis and Briggs (1989) have used this capability to analyze the degree of textural contrast within different landscape units of the Konza Prairie Research Natural Area, but to our knowledge this technique has not previously been used to analyze the boundaries *between* landscape units (i.e., the ecotones). Textural analysis can be done with any digital representation of continuous variation over space (e.g., a digital elevation model, band ratioed Landsat data) using the moving window scan utility of raster-based GISs such as MAP (Tomlin, 1983) and ERDAS (ERDAS, 1987).

In addition to their potential for locating ecotones, GISs can be used to measure ecotone length, density (length of ecotone per unit area), or fractal dimension (Krummel *et al.*, 1987). Ecotone length can be measured directly using a vector-based GIS, or can be estimated using the pixel dimension on a raster-based GIS (Johnston and Naiman, 1989). Therefore, Geographic Information Systems (GIS) are expected to become important tools for the quantitative study of ecotones (Johnston *et al.*, 1989).

The purpose of this paper is to report on experiments designed to evaluate GIS techniques for detecting, classifying, and measuring ecotones. Specific objectives are (1) to use GIS with image classification techniques to detect, classify, and measure ecotones among plant communities, and (2) to use GIS and image analysis techniques to detect and quantify local ecotones related to green vegetation biomass.

METHODS

STUDY AREA

The Horsehead Lake area in north central Minnesota (47° 40′ N, 93° 17′ W) was used as a study area. It lies in the Northern Lakes and Forests ecoregion of the United States (Omernik, 1986) and is part of the George Washington State Forest. Although the area is predominantly forested, it contains many naturally occurring patches (Pickett and White, 1985) of lake, wetland, and upland vegetation. Aspen (*Populus* spp.) and paper birch (*Betula papyrifera*) are the predominant deciduous species, while pine (*Pinus* spp.), spruce (*Picea* spp.), and balsam fir (*Abies balsamea*) are the major conifers. Disturbance by beaver

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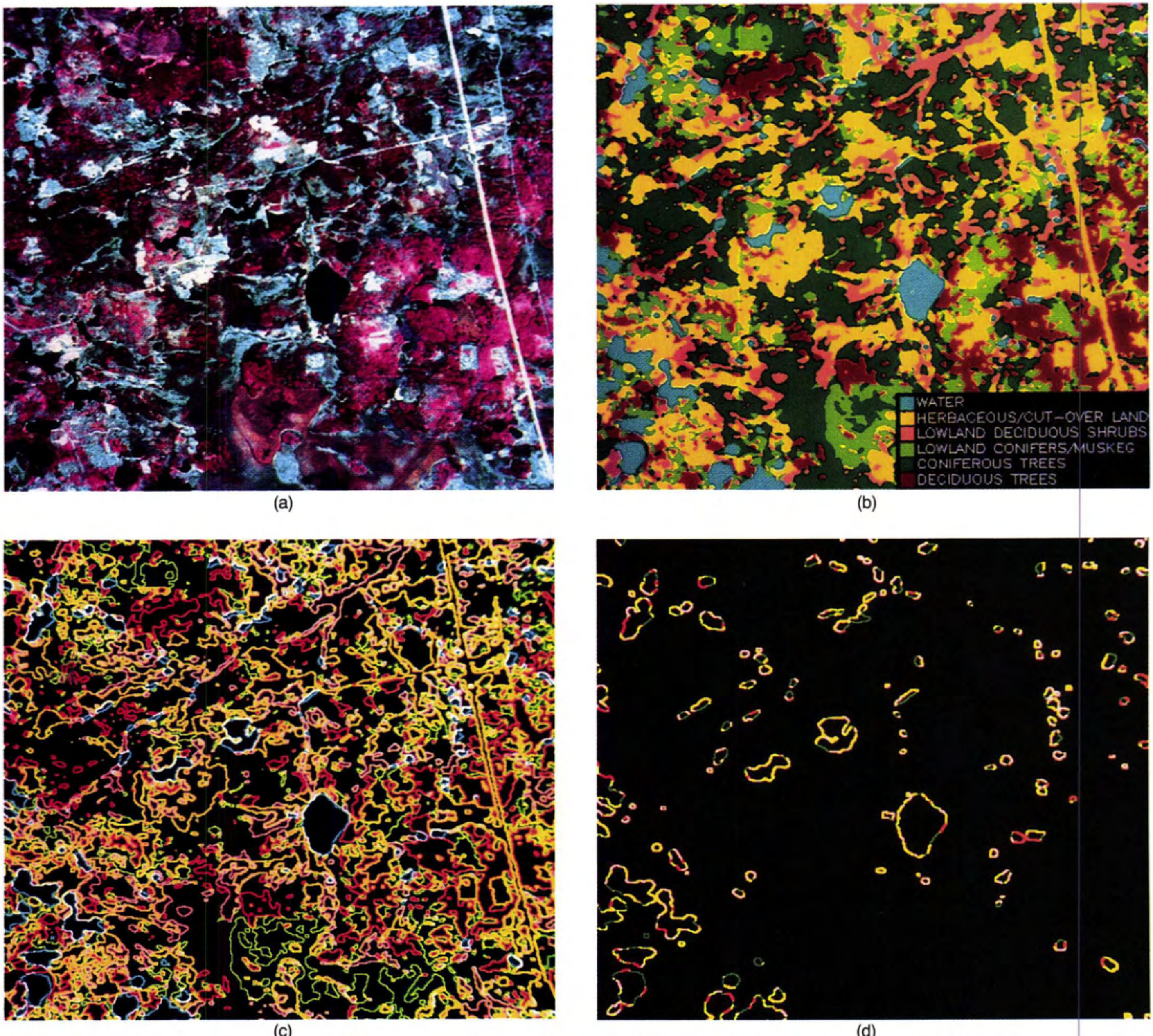


PLATE 1. Ecotone detection using a combination of remote sensing and GIS techniques. (a) Landsat thematic mapper image (bands 2, 3, and 4) of a 324 km^2 area of north central Minnesota, taken 18 May 1984. The linear feature on the right side of the image is a pipeline. (b) Land cover map derived from the image. (c) Ecotones between land cover patches. Each ecotone is two pixels wide, consisting of one pixel from each of the adjoining patches. (d) Ecotones surrounding water bodies, by land cover class.

impoundments and man (logging, vacation homes, pipeline construction) have created numerous open patches in the forest matrix. The abundance of natural and man-made patches makes it an excellent site to study ecotones.

DATA ANALYSIS

Two raster-based GIS packages were used for the analysis: ERDAS (ERDAS, 1987), a microcomputer-based combination GIS/image analysis system, and EPPL7 (EPPL7, 1987), a raster-based GIS developed by the Land Management Information Center (LMIC) of the Minnesota State Planning Agency. Data were exchanged between the two systems using a program written by Anderson and Scheer (1987).

Ecotones between plant communities were analyzed using a 324 km^2 Landsat Thematic Mapper (TM) scene taken 18 May 1984 (Plate 1a). Bands 2 (0.52 to 0.60 μm), 3 (0.63 to 0.69 μm), and 4 (0.76 to 0.90 μm) were used with an unsupervised clustering routine to classify the area into 27 initial categories. The 27 initial clusters developed were grouped into six general land cover categories using ground truth from 1:24,000-scale aerial photography of the same area. Although a similar cover map could have been constructed by manually interpreting and delineating the aerial photos themselves, the TM-derived map was preferable because the data were already in digital form and because computer classification is more objective than human interpretation. A 3 by 3 moving window (the ERDAS "SCAN" routine) was used to smooth the classified image by assigning the modal value to the central pixel of each window, thereby smoothing the image by removing patches < 0.5 ha (Plate 1b).

The moving window was also used to locate boundaries between the land cover classes. The data layer was scanned with a 3 by 3 pixel moving window using the boundary option of the ERDAS SCAN routine. A value of 0 was assigned to any non-boundary pixel, and the value of the land cover class to pixels at the boundaries of the land cover patches. The resulting boundaries were two pixels wide, showing the land cover classes present on both sides of each ecotone (Plate 1c).

While the above analysis provided a good graphical depiction of ecotone location and type, it could not be used to classify boundaries according to the types of land cover classes which they separated. This was accomplished by creating a separate data layer for each land cover class. As each cover was selected, all other cover types were recoded to 0. A one-pixel buffer surrounding each polygon in the selected cover class was created with the ERDAS "SEARCH" command, and used to extract data from the original cover map with the ERDAS "MATRIX" command. The result was an edge map of all land cover types adjoining polygons of the selected cover type (Plate 1d).

Ecotones between areas of high and low vegetation biomass were analyzed using the same Landsat scene. A normalized difference vegetation index (NDVI), which is related to green vegetation biomass (Tucker, 1979), was computed for each pixel in the image (Figure 1a) using the following formula:

$$\text{NDVI} = (x4 - x2)/((x4 + x2) + 0.5)$$

where NDVI = normalized difference vegetation index,
x4 = brightness value from infrared band 4, and
x2 = brightness value from red band 2.

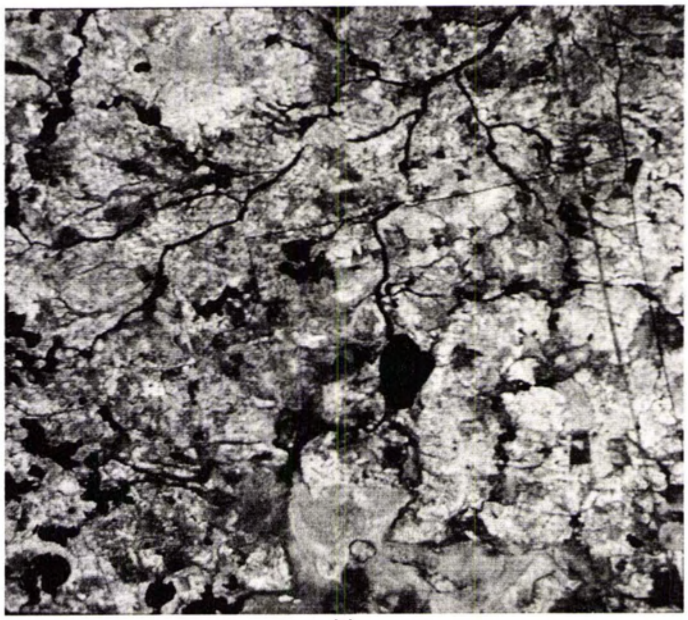
Ecotones between areas of high NDVI (i.e., high biomass) and low NDVI (i.e., low biomass) were determined using EPPL7 to scan the resultant image with a 3 by 3 pixel moving window which assigned the difference between the maximum and minimum value in the window to the central pixel, thus identifying areas of high NDVI contrast (Figure 1b).

RESULTS

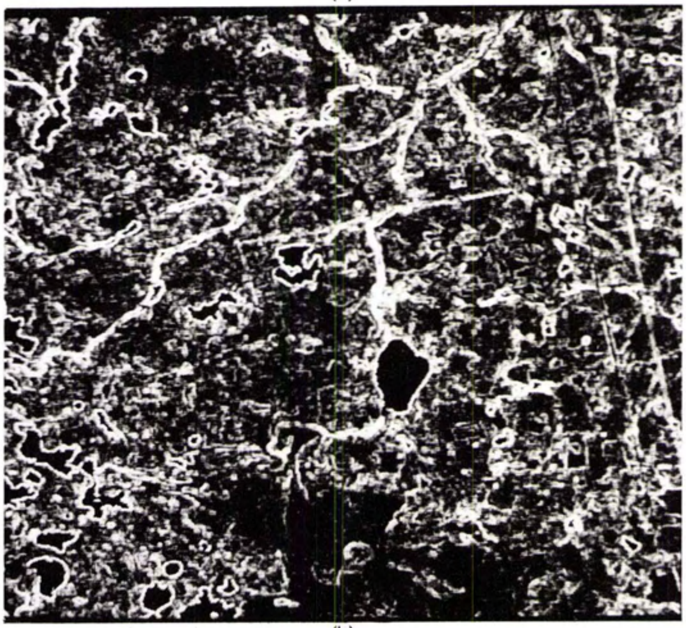
About 5,900 km of ecotones between major vegetation types were detected using the land cover data layer generated by means of satellite data analysis (Table 1). Patches of coniferous trees had the longest cumulative boundary length (1,550 km), followed by muskeg (1,173 km) and herbaceous patches (1,059 km). The four longest individual boundary classes were also between conifers and other land cover types: conifer/muskeg, conifer/deciduous, conifer/shrub, and conifer/herbaceous (Table 1). This was expected, based on the predominance of the conifer land cover type (Plate 1b).

Ecotones with water bodies had the shortest cumulative length, 270 km. It is interesting to note, however, that water bodies share more border with lowland shrub patches than with any other cover type, even though all other boundary classes have longer cumulative lengths than that of lowland shrubs. The length of water/shrub ecotone is approximately twice the length of water/deciduous ecotone, despite the fact that shrub and deciduous forest patches had equivalent total ecotone lengths. This indicates a preferential association between water and lowland deciduous shrubs. At a broader scale, the lowland deciduous shrub patches constitute an ecotone between water and upland.

While the above technique was useful for detecting, classifying, and measuring ecotone length, it provided no information about relative differences in the ecological properties of adjacent patches. For example, there is a large difference in the biomass of a lake as opposed to a forest, so the ecotone between



(a)



(b)

FIG. 1. (a) Vegetation index computed from bands 2 and 4 of a Landsat thematic mapper image of north central Minnesota (Plate 1a). High intensity pixels have high NDVI values. (b) Ecotones between areas of high and low vegetation productivity derived by scanning the above image. High intensity pixels occur where the contrast among NDVI values in the 3 by 3 pixel scan window was greatest.

these two classes would be a high contrast ecotone (Holland, 1988). Scanning the NDVI image with a maximum-minimum window provided a measure of ecotone contrast, with low values signifying homogeneity within the window (i.e., no ecotone) and high values signifying large differences in NDVI within the window (i.e., a high contrast ecotone). Therefore, ecotones between lakes and upland forest appear as bright borders on the scanned NDVI image, while the lakes themselves and areas of homogenous muskeg vegetation are uniformly dark due to the lack of variation among NDVI values. Other distinct boundaries detected by this technique include boundaries between

TABLE 1. LENGTH OF BOUNDARIES BETWEEN DIFFERENT LAND COVER CLASSES SHOWN IN PLATE 1B, BY BOUNDARY TYPE.

	Length of boundary (km) with:					
	H2O	HERB	SHRUB	MUSKEG	CONIF	DECID
Water (H2O)	–	65	69	41	61	35
Herbaceous/cut-over (HERB)		–	276	259	314	145
Low deciduous shrubs (SHRUB)			–	152	375	50
Low conifers/muskeg (MUSKEG)				–	411	311
Coniferous trees (CONIF)					–	389
Deciduous trees (DECID)						–
Total boundary length (km)	270	1059	923	1173	1550	931
Percent of total boundary	4%	18%	16%	20%	26%	16%

areas of upland forest (high biomass) and lowland deciduous shrubs or herbaceous areas (Figure 1b) (low biomass).

DISCUSSION

We found that analysis of remotely sensed imagery using a raster-based GIS provided ecotone detection and quantification capabilities which would have been more difficult to impossible without a GIS. While ecotones between land cover types can be detected by conventional mapping methods (e.g., field surveys, air photo interpretation, delimiting vegetation range maps), GIS analysis of remotely sensed imagery was more objective than conventional methods. Both conventional and GIS methods may be equally effective at detecting ecotones in areas where the magnitude of ecological change is large and abrupt, but the GIS also detected ecological transitions which were more subtle, such as those between different forest types. A GIS is also more likely to detect ecotones surrounding small patches which would be difficult and time-consuming to delineate manually.

Conventional vegetation maps generally differentiate dissimilar ecological patches, rather than characterize the ecotones themselves. Although the boundaries drawn on the maps constitute ecotones, only the patch contents are classified and quantified. The GIS provided the ability to classify ecotones by the cover types which they separated, and to measure the length of those different ecotone classes. While we used remotely sensed imagery as our source data, the moving window boundary analysis could be applied to any rasterized map with nominal data, such as land cover maps in the USGS LUDA series.

This ecotone analysis provided new insights about the association of different land cover types (i.e., water and lowland deciduous shrubs). The application of statistical techniques, such as electivity index, to these data could provide a more quantitative analysis of the strength of ecological associations and disassociations between cover types (Pastor and Broschart, 1989).

The moving window approach was also applicable to rasterized interval data, in this case the NDVI data layer. Not only was this approach suitable for locating ecotones, it also provided a measure of ecotone contrast. This could be used to identify areas where fluxes across ecotones may be important. For example, input of allochthonous organic matter fom upland to stream constitutes a large proportion of the stream's carbon budget, due to the stream's inherently low productivity relative to upland ecosystems. Therefore, high contrast ecotones on the scanned NDVI image, such as those between water and upland, may indicate areas of high biomass flux between ecosystems.

We analyzed a single date of imagery, but the moving window technique could be used with a time series of images to determine boundary stability. For instance, the ecotones between different land cover types (Plate 1c) are relatively stable on an annual basis, changing only with disturbance. Some boundaries may be more ephemeral, however, such as the difference in NDVI between lowland deciduous shrubs and upland forest. Upland vegetation greens up faster in the spring than does wetland vegetation, so biomass ecotones detected using an 18 May 1984 image would probably diminish later in the growing season as wetland biomass approaches that of its upland counterparts. By integrating NDVI values over an entire growing season, ecotones between areas of high and low net primary productivity (i.e., process-related ecotones) could be identified (Goward *et al.*, 1986).

Where the locations of ecological boundaries are already known, GIS techniques can be used to characterize ecosystem properties adjacent to the boundary, such as land cover adjacent to streams. This buffering technique has been combined with field data to investigate the effect of streamside land uses on stream water quality (Johnston *et al.*, 1988; Osborne and Wiley, 1988).

Ecotone classification and measurement is operationally much simpler using a vector-based than a raster-based GIS. Vector-based systems such as ARC/INFO automatically determine which polygons adjoin an ecotone when topology is created for the coverage. Ecotone lengths can therefore easily be summarized by the land cover classes which they separate. The advantage of using raster-based systems, however, is that they can use image analysis to detect ecotones, while ecotone location in a vector-based system is pre-determined by the input data (i.e., the digitized linework). Furthermore, raster-based GISs can be used with interval data to analyze ecotone contrast, a capability lacking in vector-based systems.

The resurgence of interest in ecotones has come at a technologically opportune time. The evolution of GIS equipment and methods over the past decade have greatly increased our ability to quantitatively study ecotones. This ability will be essential to the development and testing of scientific theories pertaining to ecotones.

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