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ANALYZING LONG-TERM CHANGES IN VEGETATION WITH GEOGRAPHIC INFORMATION SYSTEM AND REMOTELY SENSED DATA

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ABSTRACT

Geographic information systems and remote sensing techniques are powerful tools in the analysis of long-term changes in vegetation and land use, especially because spatial information from two or more time intervals can be compared more readily than by manual methods. A primary restriction is the paucity of data that has been digitized from earlier periods. The Illinois State Geographic Information System has a number of automated data sets containing land-use information, including original land survey plat maps that show the boundaries of forests, prairies, and wetlands as they existed prior to European colonization in the early 1800s. More recent data include the United States Forest Service inventories of 1948, 1962, and 1985; the United States Geological Survey Land Use Data Analysis; National High Altitude Program photographs of vegetation; and Landsat MSS and TM information. These data can be used to compare vegetation patterns and changes in land use over time and to suggest factors that may have caused or influenced these variations. Profound changes have occurred in the Illinois landscape since European settlement, primarily because of conversion to agricultural use; in certain parts of the state, however, urbanization has been the major factor contributing to changes.

INTRODUCTION

The assessment of long-term changes in vegetation is a vital prerequisite to the detection of changes in the global carbon cycle, and satellite image analysis is the preferred method for determining rates of deforestation and reforestation over wide geographical areas /1/, /2/. Information about changes in local vegetation is also of value to those interested in such topics as the history of settlement, ecological succession, the preservation of natural systems, and human impacts on the landscape. Approximately 40% of the Earth's land area has been substantially modified from its presettlement state by humans /3/, and 34% of the coterminous United States has been converted to land uses other than Kuchler's potential natural vegetation /4/. Massive land conversions continue, with the result that the undisturbed habitats vital to the maintenance of biotic diversity /5/ are being lost, and many of the ecological functions of the landscape can no longer be supported.

Geographic information systems (GIS) are rapidly becoming highly important tools for natural resource research and management. The technology is advancing quickly in all phases, from vector-based systems to raster-based systems, and from small, PC-based systems to large, main-frame systems /6,7/. The integration of image analysis capability with GIS further enhances the utility of GIS technology /8/. Applications of GIS vary widely and encompass nearly all phases of natural resource management; a few examples include suitability for highway placement /9/, potential for soil loss /10/, siting for a large nuclear research facility /11/, mapping of prime timberland /12/ or forest productivity /13/, management of forest lands /14,15/, and determining landscape and land use relationships /16/.

Geographic information system and remote sensing technologies are useful in the assessment of changes in vegetation /1,6,9,17/. Since the earliest LANDSAT imagery dates to 1972, paired images from subsequent dates can be used to detect changes in the landscape. Aerial photography, in use since the 1930s, can be used to assess vegetation changes over relatively small areas /18/. To assess changes since European colonization, however, we must resort to maps drawn by early surveyors who relied on ground surveying equipment. The primary source of that information in the United States are Government Land Office (GLO) survey records /19/. When these original plat maps are automated into a registered GIS, however, overlay techniques can be used to make comparisons and to determine trends.

The objectives of this paper are to evaluate current and historic vegetation and land-use data for sections of the United States, to suggest methodologies for studying landscape trends using GIS technology, and to test these methodologies using Illinois data to summarize long-term vegetation trends in the state.

DATA RESOURCES

The Illinois GIS, housed at the Illinois Natural History Survey, contains state-of-the-art software and hardware for the manipulation of spatial data /20/. The software used for GIS analysis was ARC/INFO installed on a PRIME 9955 and networked to a PRIME 750 /21,22/. Image analysis was conducted on an Earth Resources Data Analysis System (ERDAS) on an IBM-PCAT.

This study relied on the following Illinois digital data bases: (1) original land surveyor plat maps produced by the General Land Office and showing forest, prairie, and wetland boundaries as they existed in the early 1800s; (2) United States Geological Survey Land Use Data and Analysis (LUDA) from the late 1970s using level II land-use classification at either 4-or 16-ha resolution for Illinois /23/; (3) National High Altitude Program (NHAP) photographs interpreted for vegetation at 1-ha resolution and digitized into the GIS; (4) 1985 United States Forest Service (USFS) inventories of the forests of Illinois; (5) LANDSAT MSS data from June 1978; and (6) LANDSAT TM data from July 1984. These data sets were integrated on a common projection to allow overlay analysis. Special efforts were taken with the GLO data to ensure cartographic and interpretative accuracy. Data from six Illinois counties are used in this paper (Figure 1). Lake County in the urbanized Chicago region has many glacial depressions interspersed. The remaining counties (Calhoun, Jersey, Jackson, Williamson, and Lawrence) are in the southern half of the state where the prairies and forests are highly interspersed and where land-use decisions have been made without the pressures of urban sprawl.

ASSESSING BIAS IN GENERAL LAND OFFICE ORIGINAL SURVEY RECORDS

The Northwest Ordinance of 1785, authored in large part by Thomas Jefferson, determined the method of survey for the recently acquired lands lying to the west of the original thirteen colonies /24/. According to this ordinance, land was to be laid out in townships consisting of 36 sections, with each section 1.6 km (1 mile) on a side. As the land was surveyed, the surveying team was instructed to record in detail the lay of the land, whether the land was fit for cultivation, and the vegetation types present. At each quarter section, the surveyors were to identify "witness trees" so that the corners could be located again at a later date. They recorded the species of each of these trees, its diameter, and its bearing and distance from the corner. They also were to draw plat maps that outlined prairie, timber, and various wetland types on township maps. These archived plat maps have been digitized for portions of Illinois. Despite their enormous potential value, these data have several limitations /25/. Because the surveyors were not botanists, inconsistent classifications of forest types and wetlands were made. They also found it difficult (as it is for us) to map boundaries separating forest and prairie when vegetation types merged. In addition, the national surveying system was not standardized until 1855, and several sets of instructions had been followed during the Illinois survey. In some instances surveying teams fraudulently manufactured plat maps and field notes without going into the field /19/! Nevertheless, these maps provide the best available data for describing the vegetation and the landscape prior to the impact of white settlers.

We were able to use the GIS to test for surveyor bias in the data and to compensate to an extent for that bias. The surveyors had walked along the section lines, recording such features as water bodies or prairie patches, that fell within their view. Small landscape features that existed entirely or largely in the interior of a section, however, were likely to be missed or underestimated. To test this hypothesis, buffers of 100, 200, and 400 meters were placed around the section lines for three counties in Illinois: Lake County, which, as its name implies, is dotted with glacial depressions; Jackson County, which borders the Mississippi River to the west; and Lawrence County, which borders the Wabash River to the east. The buffered sections were then overlaid on automated plat map data and statistically evaluated to determine if the percent of wetland inside the buffer multipled by the hectares of wetland for each section was the same as the percent of wetland outside the buffer multiplied by the wetland hectares. We tested the hypothesis further by applying the same test to the LUDA data from recent aerial photograph interpretation. The bias of GLO wetland polygons within the 200-m buffer from the section line are demonstrated for Lake County in Figure 2, with visibly more wetlands occurring on or near the section lines. Analysis of the present day LUDA data for Lake County showed no difference in the percent of wetland inside and outside the buffer (Figure 3); however, a significant difference did occur at all buffer distances for GLO inside and GLO outside the wetland areal estimates.

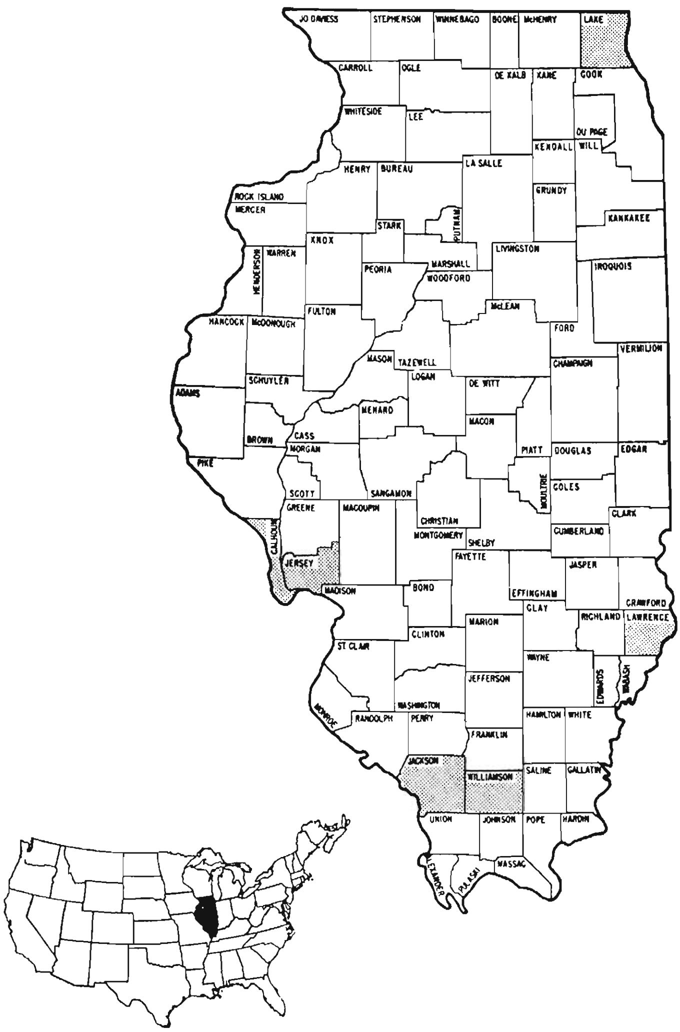

Fig. 1. Illinois counties investigated in this study.

Based on this analysis, we calculated a calibration factor that could be to applied to the GLO data to more accurately measure the wetlands at the time of settlement. Based on the calibrated data, we determined that wetlands in the three counties had been underestimated in 1820 by 20-50% (Table 1). Then, by comparison to the LUDA wetland data, we estimated the loss of wetlands between 1820-1980 to be from 59-72% in Lake, Lawrence, and Jackson counties (Table 1).

CHANGES IN VEGETATION SINCE THE ORIGINAL LAND SURVEY

In addition to the assessment of wetland loss just described, GIS overlay techniques allowed us to examine other long-term changes in land use by combining the GLO data with LUDA or other recent data sets. In this way, we assessed changes in each land type (forest, prairie, wetland, water) since 1820, the time of the original survey for the five Illinois counties listed earlier: Lake, Lawrence, Jersey, Jackson, and Williamson (Figure 1).

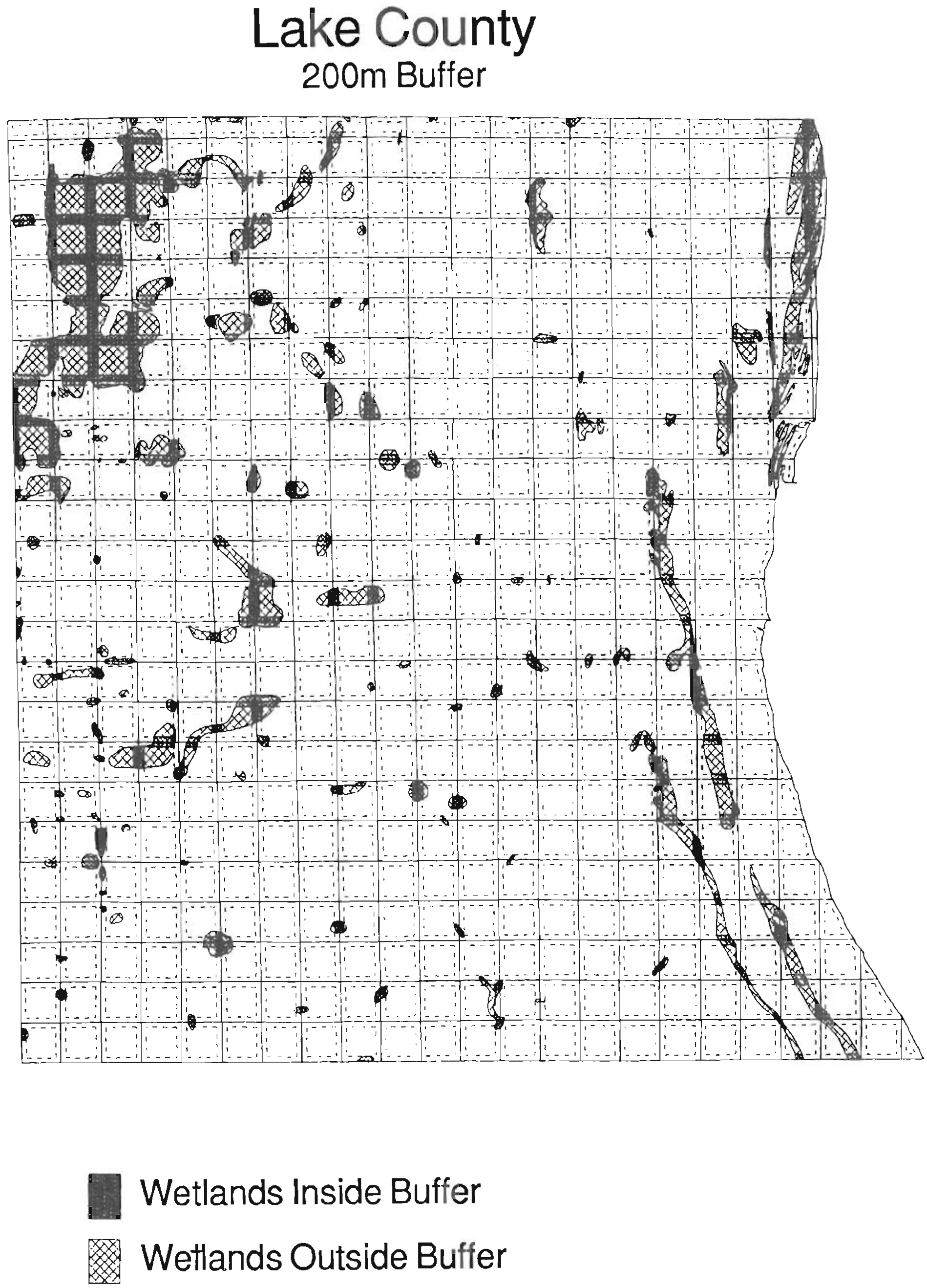

Fig. 2. Lake County, Illinois wetlands as they existed in 1840 either inside or outside the 200 m buffer line.

Land use for two of these counties, Jackson and Lake, showed dramatic changes especially with regard to diminishing forest and prairie (Figure 4). Most of the conversion in both counties has been to agriculture, although Lake County has also experienced extensive conversion to urban land uses. In Jackson County, the unconverted forest area occurs on the highly dissected bluff region along the Mississippi River. The Mississippi floodplain in western Jackson has also experienced large conversions of wetlands. In Lake County, virtually the entire eastern side bordering Lake Michigan is now urbanized, although large agricultural areas exist in the interior of the county. The changes in land use have been mapped for Lake County (Figure 5).

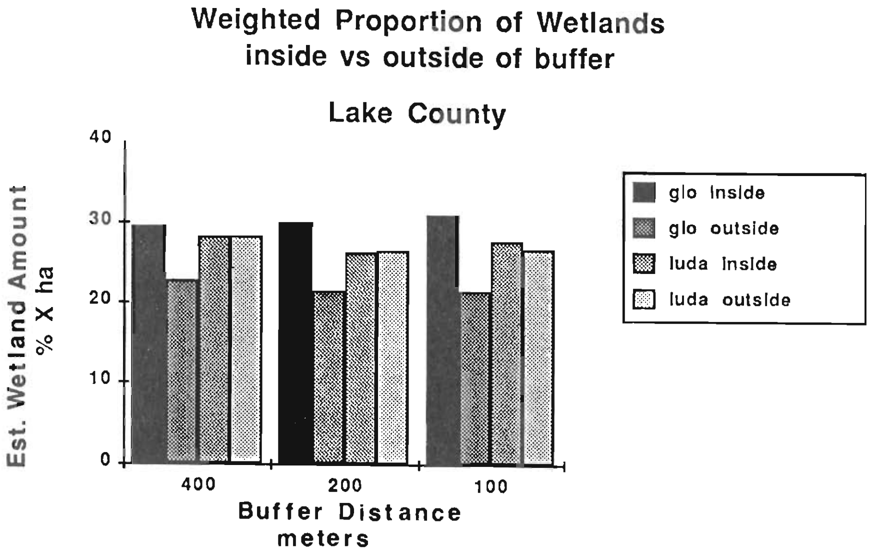

Fig. 3. Weighted proportion (% of section wetland inside or outside the buffer multiplied by the number of hectares of wetland inside or outside of the buffer) of wetlands for GLO (1840) and LUDA (1980) data for Lake County, Illinois. Pairs of GLO data differ significantly at the 0.05 level whereas pairs of LUDA data do not differ statistically.

TABLE 1 GLO Original Wetland Areal Estimates, Calibration Factors, Adjusted Areal Estimates, and Wetland Change Estimates between 1820-1980 for Three Counties in Illinois

County	GLO Original Wetlands (No. ha)	Calibration Factor	GLO Calibrated Wetlands (No. ha)	LUDA Reported Wetlands (No. ha)	Percent Change (uncalibrated)	Percent Change (calibrated)
Lake	11,175	1.20	13,410	7,786	-44	-72
Lawrence	4,810	1.50	7,215	4,540	- 6	-59
Jackson	4,550	1.24	5,642	3,317	-37	-70

Land-use change matrices are also presented for Jackson and Lake counties (Table 2). The Jackson matrix shows that 68% of the original forest is now in agriculture. Agriculture has also captured 75% of the former prairies, 72% of the GLO wetlands, and 91% of the former shallow ponds (water). The extent of large river area was only 32% of its original amount; 40% had been usurped by agriculture.

In contrast to Jackson County, each of the GLO land classes in Lake County showed a relatively high conversion rate to urban land use (Table 2); however, even in this highly urbanized county (Figure 4), agriculture captured the largest share of the conversion. Only 9% of the forest and 9% of the wetlands remain. The glacial ponds and lakes in this county are evidently deeper and less easily drained than those in Jackson County since 57% of its open water still remains (compared to only 3% in Jackson County). Conversely, 91% of the original lakes and ponds in Jackson County are now in agriculture compared to only 1% in Lake County.

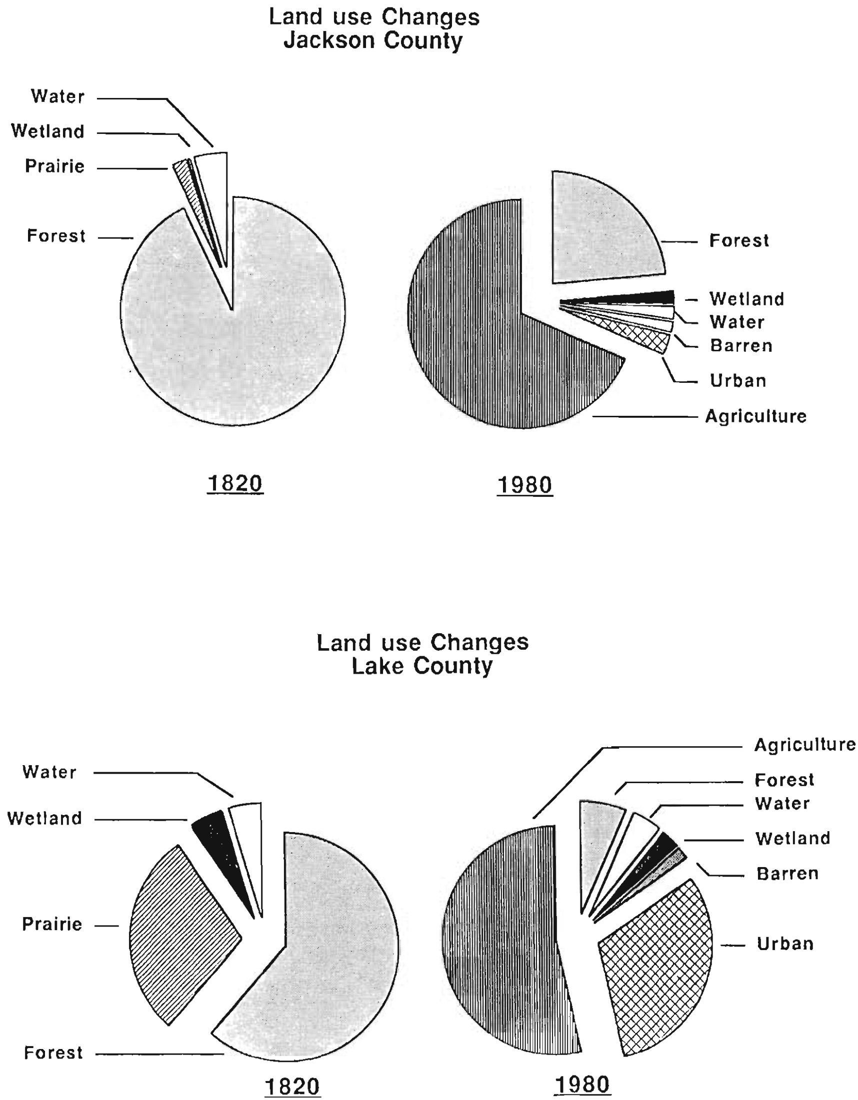

Fig. 4. Land-use trends for Jackson and Lake counties.

Each of the five counties analyzed for vegetation change since the GLO survey has experienced drastic conversions, especially to agriculture. The loss of prairie lands is essentially complete and only a few small prairie remnants remain. Prairie losses are general throughout the state. Of the original estimated 8.5 million hectares of prairie in Illinois, only about 1000 remain /26/; nearly all of the Illinois prairie is now in row crop agriculture. The loss of forest lands, while not quite as severe, is nevertheless dramatic, and only 8-55% of the original forests remain (Table 3). Most have been cleared for agriculture, ranging from 41% in Jersey County to 82% in Lawrence County.

Klopatek et al. /4/ have estimated how much of each of Kuchler's potential vegetation types in the United States have been lost /27/: an 85% loss of bluestem prairie nationwide, a 74% loss of oak-hickory forest, a 78% loss of the mosaic of these two, a loss of 83% of maple-basswood forest, and a loss of 83% of oak savanna. These five vegetation types occupied essentially all of the land area of Illinois at the time of the European colonization. The data from the present study generally agree with the national trend, although certain differences are apparent. The bluestem prairie has been eliminated to a higher degree in Illinois and less than 0.1% of the original prairie remains. Distinct variations in forest loss also occur depending on the location of a given county (Table 3).

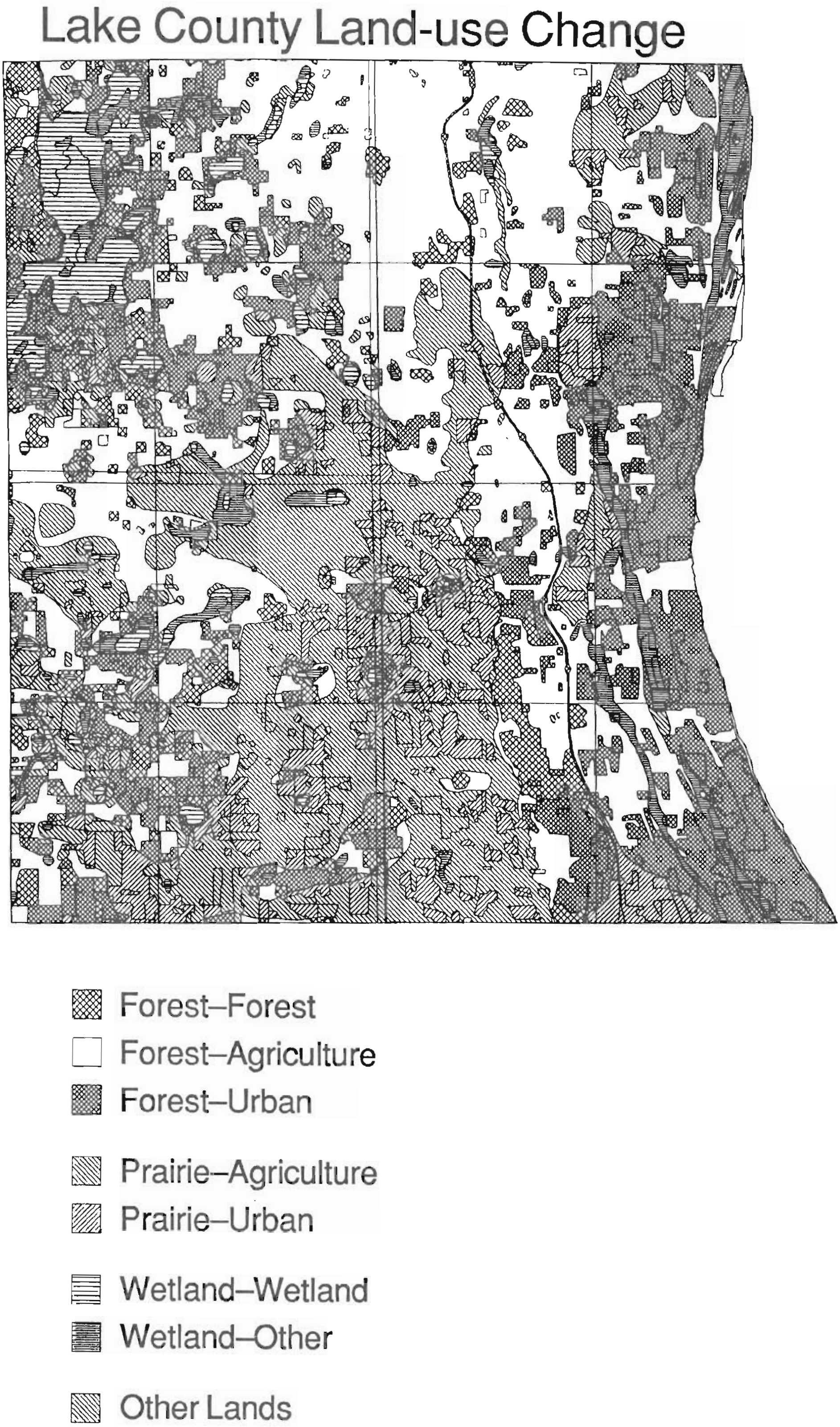

Fig. 5. Map indicating land-use trends since 1820 in Lake County, Illinois.

TABLE 2 Changes in Land Use since 1820 for Jackson and Lake Counties, Illinois. Tabular Figures are Percent of Original (GLO) Land-use Type Found in Present (LUDA) Land-use Type

Jackson County

GLO data	% Land	LUDA data Forest	Ag.	Urban	Water	Wetland	Barren
Forest	93.0	25	68	3	1	2	1
Prairie	2.0	5	75	6	<1	0	14
Wetland	0.3	7	72	0	0	21	0
Water	2.6	3	91	1	3	3	0
River	2.1	13	40	1	32	15	0

Lake County

Forest	61.4	9	52	34	2	2	1
Prairie	29.2	3	65	27	<1	1	3
Wetland	4.7	4	45	38	3	9	3
Water	4.6	5	1	16	57	15	1
River	0.1	12	20	17	40	8	2

TABLE 3 Summary of Forest Changes since 1820 for Five Counties in Illinois

County	% of GLO Forest in Present Land Use Forest	Agriculture	Urban	Other
Lake	9	52	34	5
Lawrence	8	82	5	5
Jersey	55	41	2	7
Jackson	25	68	3	4
Williamson	32	53	9	6

Jersey County, for example, has 55% of its original forest since it is topographically more dissected than Lawrence County, which has only 8% of its original forest. Statewide, approximately 37% of the forest acreage present when the white settlers arrived remains. Of course, a large proportion of the present forest cover is secondary growth since settlement times. Although the loss of forest in Illinois is slightly smaller than the national trend, the loss of prairie in the state has been substantially greater. Overall, Illinois has had the second highest land conversion in the nation with only 11% of its area remaining in its Kuchler potential natural vegetation types /4/.

WITNESS TREE ANALYSIS

The GLO surveyors recorded species, size, distance, and bearings for up to four trees from each section and quarter section corner /28/. These witness trees were normally located within 30 meters of the corner in forested regions and were scribed to help identify the corner placement. Our objective here was to compare the rates of forest conversion between upland and bottomland forest types for Williamson County. To accomplish this, the two points (trees) from each quarter section corner were categorized as either bottomland or upland forest. Admittedly, two trees at each point were insufficient to characterize the vegetation with great confidence, although most species can be separated as upland or bottomland species. About 90% of the points were readily assigned to upland or bottomland based on the two trees; the remaining points had mixed species types. The mixed points were also assigned as bottomland for this demonstration, although the trends were found to be similar when the mixed points were excluded.

The resulting points, classified as upland or bottomland (corner locations), were then intersected with a soils map and the LUDA land-use map for Williamson County. The LUDA information was used to describe present-day forests and the soil information was used to divide the landscape into upland or bottomland. These processes allowed us to calculate the conversion rates of bottomland vs. upland forest types since the GLO survey (Table 4). These data show little change in proportion of upland to bottomland or in the percentage of overall conversion. About 13.5% of the original upland forest and 14.6% of the bottomland forest continue to exist. Current evidence suggests that bottomlands are presently being converted from forests at a higher rate and that some highly eroding uplands are reverting to forests /29/. The advisability of clearing of bottomlands in Illinois is problematic because clearing reduces valuable wildlife habitat, increases soil loss through water erosion, and reduces flood water storage along river systems /30/.

TABLE 4 Percentage of Witness Trees on Upland or Bottomland Soil Types in 1820 and 1980 and the Percentage of Those Points Remaining in Forest

Soil Type	% of Witness Trees 1807	1980	% Remaining in Forest
Upland	73.4	71.0	13.5
Bottomland	26.6	29.0	14.6

UNITED STATES FOREST INVENTORY

The United States Forest Service periodically inventories the forest resources of the country and inventories were conducted in Illinois in 1948, 1962, and 1985. Each township was hierarchically sampled with over 100 photograph interpretation points and about 6 ground plots per township. Since the ground plots are remeasureable, we can assess vegetation changes since the previous inventory. Variables from these inventories that can be used to describe vegetation change include basal area change and stand history /31/. Obviously, if specific plot data were available for more than one measurement date, additional detection of forest change would be possible using a number of variables including composition, volume, and green tons biomass. However, no specific plot data were available for the 1962 measurement.

One variable in the Forest Service data base assesses changes in forest stand since the previous measurement (1962 in this case). Of the 341 ground plots located in the southern fifth of Illinois, 43 (13%) had experienced some kind of stand disturbance or change in the past 23 years. Broken down further, 2 plots had seen timber stand improvement, 2 had been clearcut, 21 had been partially harvested, 5 had been hit by fire, insects, or disease, 4 had been otherwise disturbed by man (e.g. spraying or drainage), and 9 had naturally regenerated from nonforest land since 1962.

In an attempt to understand the relationship of stand change to landscape environment, the plot locations were overlaid with a general soils map for southern Illinois. Basal area changes of stands since 1962 were calculated for the 341 ground plots and these changes were then compared to soil parent material types. In general, total basal area of stands on bottomland soils increased more than total basal areas of stands on upland soils. Seventy-one percent of the bottomland plots increased their basal area by more than 2 sq. ft./acre/year; only 37% of upland soil plots accumulated at that rate. The power of point-in-polygon overlay in the GIS is exemplified here where tabular, site-specific information can be related to the landscape and summarized. GIS processing can also be used to estimate forest acreage and volume more accurately by relating soils, land use, or LANDSAT imagery to the ground plot data.

LANDSAT CHANGE DETECTION

Multitemporal Landsat data can be used to detect change in vegetation over time. Such changes are valuable in evaluating the global carbon cycle /1/, in conducting forest timber inventories, and in managing wildlife habitat /17/. Most studies that describe vegetation change thus far have been done using MSS data alone. In our example, we combined MSS data from 4 June 1978 with TM data from 9 July 1984 for a heavily forested portion of southwestern Illinois in Calhoun and Jersey counties. MSS data were unavailable for the 1984 date, and we wanted to focus on differences and similarities between the abilities of TM and MSS to detect change. Because of differences in spectral and spatial resolution, independent processing was conducted with image combination as the final step. Both data sets were registered to UTMs to within one pixel accuracy. The MSS data were resampled to 30 m pixel size to match the TM data. An unsupervised classification algorithm was used to classify each data set to 50 clusters, and these clusters were aggregated into forest or nonforest classes. The two data sets were then combined to form a third image with five MSS-TM (1978-1984) classes: (1) forest-forest, (2) forest-nonforest, (3) nonforest-forest, (4) nonforest-nonforest, and (5) water. In our definition of nonforest here we exclude water.

Results of this preliminary analysis yielded information on forest changes (Table 5). Approximately 12% of the land has changed from forest to nonforest, either by timber harvest or by conversion to other land uses. Conversely, about 7% of the land has been converted from nonforest or has successionally grown up to be classed as forest. Most of the forest loss has occurred in the bottomlands of the Illinois and Mississippi rivers. The net loss of forest is disturbing in Illinois where we have seen massive conversion of forest to agriculture, with consequent increases in soil erosion and decreases in water quality and wildlife habitat.

TABLE 5 Detection of Forest Changes in Calhoun and Jersey Counties using MSS from 4 June 1978 and TM from 9 July 1984.

Description	Ha	Percentage
Forest-Forest	10,060	38
Forest-Nonforest	3,330	12
Nonforest-Forest	1,840	7
Nonforest-Nonforest	6,350	24
Water	5,200	19

CONCLUSIONS

This study has analyzed changes in land use and vegetation in parts of Illinois and has suggested how GIS and remote sensing tools can assist in such efforts. These technologies allow data to be processed spatially so that current land use on individual land parcels can be evaluated in conjunction with historical information on that parcel. This type of comparison is a considerable improvement over the analysis of summary statistics deduced from sampling methods that do not retain the integrity of the spatial location of sample plots. Of course, caution is required in overlay analysis so that cartographic and digitizing errors at the data entry stage do not translate to information that is unquestioned at the output stage /32/. The major prerequisite for accurate long-term vegetation analysis is access to quality, map-registered data sets that can be used in digital form. The Illinois GIS is fortunate in having much of this type of information.

The GIS overlay techniques facilitated the evaluation of land-use changes over various parts of Illinois, an intensely managed part of the North American continent. Loss of natural habitat has been dramatic. The techniques described in this paper now allow us to evaluate changes in land use on a site-specific basis. This site specificity will permit land-use changes to be evaluated in an historical perspective and will allow planning decisions to be made in the context of a dynamic data base capable of tracking constantly changing patterns of land use.

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