Tracking Fragmentation of Natural Communities and Changes in Land Cover: Applications of Landsat Data for Conservation in an Urban Landscape (Chicago Wilderness)

YEQIAO WANG* AND DEBRA K. MOSKOVITS†‡

Department of Anthropology, University of Illinois at Chicago, Chicago, IL 60607-7139, U.S.A.
†Environmental and Conservation Programs, The Field Museum, 1400 S. Lake Shore Drive, Chicago, IL 60605-2496, U.S.A., email dmoskovits@fmnh.org

Abstract: *Greater Chicago is home to a surprisingly high concentration of globally significant natural communities. Within the metropolis survive some of the world's best remaining examples of eastern tallgrass prairie, oak savanna, open oak woodland, and prairie wetland. Chicago Wilderness is more than 81,000 ha of protected areas in the urban and suburban matrix. It also is the name of the coalition of more than 110 organizations committed to the survival of these natural lands. The long-term health of these imperiled communities depends on proper management of the more extensive, restorable lands that surround and connect the patches of high-quality habitat. Information critical to the success of conservation efforts in the region includes (1) a current vegetation map of Chicago Wilderness in sufficient detail to allow quantitative goal setting for the region's biodiversity recovery plan; (2) quantified fragmentation status of the natural communities; and (3) patterns of land-cover change and their effects on the vitality of communities under threat. We used multispectral data from the Landsat thematic mapper (October 1997) and associated ground truthing to produce a current vegetation map. With multitemporal remote-sensing data (acquired in 1972, 1985, and 1997), we derived land-cover maps of the region at roughly equivalent intervals over the past 25 years. Analyses with geographic information system models reveal rapid acceleration of urban and suburban sprawl over the past 12 years. Satellite images provide striking visual comparisons of land use and health. They also provide banks of geographically referenced data that make quantitative tracking of trends possible. The data on habitat degradation and fragmentation are the biological foundation of quantitative goals for regional restoration.*

Rastreo de la Fragmentación de Comunidades Naturales y de Cambios en la Cobertura de Suelo: Aplicaciones de Datos de Landsat para la Conservación en un Paisaje Urbano (Chicago Wilderness)

Resumen: *En Chicago hay una concentración de comunidades naturales globalmente significativas sorprendentemente alta. En la metrópolis sobreviven algunos de los mejores ejemplos mundiales remanentes de praderas de pastos orientales, sabanas de roble, bosques abiertos de roble y humedales de pradera. Chicago Wilderness es más de 81,000 ha de áreas protegidas en la matriz urbana y suburbana. También es el nombre de una coalición de más de 110 organizaciones dedicadas a la supervivencia de esas tierras naturales. La salud a largo plazo de estas comunidades amenazadas depende del manejo adecuado de las tierras, más extensas y restaurables, que rodean y conectan a los fragmentos de hábitat de alta calidad. La información crítica para el éxito de los esfuerzos de conservación en la región incluye: (1) un mapa actualizado de la vegetación de Chicago Wilderness con suficiente detalle para que la definición de metas cuantitativas para el plan de re-*

‡*Address correspondence to D. K. Moskovits.*
**Current address: Department of Natural Resource Sciences, University of Rhode Island, Kingston, RI 02881, U.S.A., email yqwang@uri.edu*
Paper submitted April 5, 2000; revised manuscript accepted January 31, 2001.

cuperación de la región sea posible; (2) cuantificación de la fragmentación de las comunidades naturales y (3) patrones de cambio de cobertura de suelo y sus efectos sobre la vitalidad de las comunidades amenazadas. Utilizamos datos multiespectrales del mapeador temático Landsat (octubre 1997) y verificaciones de campo asociadas para producir el mapa actualizado de vegetación. Con datos de percepción remota multitemporales (obtenidos en 1972, 1985 y 1997), derivamos los mapas de cobertura de suelo en la región en intervalos equivalentes en los últimos 25 años. El análisis de los modelos SIG revela una rápida aceleramiento del crecimiento urbano y suburbano en los últimos 12 años. Las imágenes de satélite proporcionan comparaciones visuales notables del uso y condición del suelo. También proporcionan bancos de datos referenciados geográficamente que hacen posible el rastreo de tendencias cuantitativas. Los datos de degradación y fragmentación del hábitat son la base biológica de metas cuantitativas para la restauración regional.

Introduction

Huge as it is, Chicago is a microcosm of some of the greatest challenges to the survival of Earth's biological diversity and to the quality of human life. Within the Chicago metropolitan region survive some of the world's best remaining examples of grasslands, woodlands, and wetlands of the eastern tallgrass prairie and grove region. Chicago's human inhabitants enjoy some of the richest cultural diversity and economic resources of any urban area on the globe. Yet pressures on the region's aquatic and terrestrial systems are rapidly eroding the vitality of its natural communities, implying present and future losses to human communities as well. Unplanned urban growth and suburban sprawl are among the main contributors to this accelerated degradation of natural communities and to the deterioration of human living conditions. Organizations in Chicago's metropolitan region are linking efforts to reverse these trends.

The Chicago Wilderness Approach

In 1996, 34 Chicago organizations joined together to protect, restore, and manage the globally prominent natural communities of metropolitan Chicago by fostering their compatibility with the human communities whose lives they enrich. Under the umbrella of the Chicago Region Biodiversity Council, this alliance of diverse and determined institutions—including local, state, and federal government agencies, landowners, research institutions, and conservation organizations—now involves more than 110 members. The focus of the coalition is Chicago Wilderness, a regional nature reserve encompassing 81,000 ha of protected lands and waters connected by greenways and wildlife corridors. It extends in a crescent around Lake Michigan, from southeastern Wisconsin, through Illinois, into northwestern Indiana (Fig. 1).

Because the natural remnants of highest integrity are small and isolated, their long-term viability depends on proper management of the surrounding areas. The Regional Biodiversity Recovery Plan, developed by the coalition and adopted by state and local planning agencies, recommends goals and strategies that scale from these individual natural remnants to the metropolitan region as a whole. Satellite images and geographic information systems (GIS) allow analysis of threats and conservation success across these geographic scales and across time.

Recognizing the critical role remote sensing can play in the health of the Chicago region's wild wealth, the National Aeronautics and Space Administration (NASA) supported a major effort in Chicago Wilderness to track changes in land cover from 1972 to 1997. Our goals for this project were to (1) complete a current vegetation map of Chicago Wilderness in sufficient detail to be useful to the regional biodiversity recovery plan; (2) examine changes in land use and land cover over the past 25 years and highlight the most severe threats to the region's globally important natural remnants; and (3) integrate the resulting vegetation map and data into the biodiversity recovery plan and into the GIS database of Chicago Wilderness. Results of this project point toward future patterns so that conservation action can be taken before change outstrips adaptability.

Satellite Images and Conservation

Remote sensing is well documented as an effective tool for mapping and characterizing cultural and natural resources (e.g., Holz 1985; Lo 1986; Jensen 1996; Campbell 1997). The multispectral capabilities of remote sensing allow observation and measurement of biophysical characteristics (Reeves 1975; Colwell 1983), and the multitemporal and multisensor capabilities allow tracking of changes in these characteristics over time. These capabilities also make remote sensing useful for evaluating results of different land-management techniques (Quattrochi & Pelletier 1991). At the regional level, the potential advantages of satellite images over aerial photographs or videography for detecting change include cost effectiveness, more coverage, and the ability to reveal landscape processes at larger scales.

A common use of satellite data is production of land-cover maps that indicate landscape pattern and process (M. G. Turner 1990; S. J. Turner et al. 1990; Baker & Cai 1992). Because most of the indices developed to characterize landscape patterns (O'Neill et al. 1988; Olsen et al.

1993; Ritters et al. 1995) are sensitive to spatial resolution and to the number of attribute classes (M. G. Turner 1990), the following criteria are critical for accurate landscape characterization: (1) appropriate classification system for clearly defined natural communities, (2) spectral uniqueness of these natural communities in remotely sensed images, and (3) accurate classification algorithms in GIS.

Methods

To produce a vegetation map for the Illinois and Indiana portions of Chicago Wilderness, we used multispectral data from two Landsat thematic mapper (TM) scenes—northeastern Illinois (023/031) and northwestern Indiana (022/031), acquired on 10 and 19 October 1997, respectively—and carried out extensive field surveys. We rectified (aligned geometrically) the two digital images and georeferenced them to universal transverse mercator (UTM) map coordinates. The interpreted composite of the two 1997 Landsat TM images covers the eight-county area of focus (Fig. 1). The six northeastern Illinois counties (Cook, DuPage, Kane, Lake, McHenry, and Will) and the two northwestern Indiana counties (Lake and Porter) encompass the city of Chicago and its suburbs.

We based the classification of the digital images on the regional community classification system developed by Chicago Wilderness (1999) (Table 1). We identified training signatures on the 1997 Landsat TM data. These color "hallmarks" tie characteristic patterns of reflectance to individual types of natural communities. In spring and summer of 1998, we undertook intensive ground truthing and botanical transects to assist in the training-sample selections. We identified locations of all ground-truthing data with a global positioning system (GPS). The GPS data were differentially corrected, projected to UTM coordinates, and converted into GIS format. After differential corrections, the spatial accuracy of the GPS data was within 1 m. We referenced field notes and GPS data to locate and define training signatures of categories for natural and cultural (human-dominated) land cover. We then applied the training signatures to classify the Landsat images.

We focused the trends analysis on fragmentation and loss of habitat over the past quarter century in the six northeastern Illinois counties only. For the analysis, we derived land-cover maps of the region at nearly equivalent intervals over the past 25 years (1972, 1985, 1997). We started with the earliest cloud-free data available for the Chicago region: a Landsat Multispectral Scanner (MSS) image (80-m spatial resolution) of October 1972. The other two images used for comparisons were both acquired by Landsat TM (30-m spatial resolution). The most recent image is from October 1997 (our project started in November 1997). Because of limited availability of cloud-free data, the midpoint image is from May 1985. Although we noticed seasonal differences among the images selected, these phenological differences are insignificant at the generalized level of our analyses of land-cover change.

We obtained historical land-cover information by referencing historical aerial photograph, U.S. Geological Survey topographic maps, and county land-management records to select training signatures for classification of the 1972 MSS and 1985 TM data. The MSS and TM data were geometrically rectified by selected ground control points and transformed into UTM coordinates. In the rectification process, we used the cubic convolution algorithm to resample the MSS data into the same spatial resolution as the Landsat TM data. The root mean square error (RMSE) among the selected ground control points was <1 m. Through visual examination we found that the final geometric matching error among these images was within one TM pixel. We then used supervised classification and maximum-likelihood classification algorithms to process the images.

Results

Classification of Digital Images and Mapping of Land Cover

The Chicago Wilderness regional classification system has eight major community classes. These are divided into 20 natural and 4 cultural (human-dominated) vegetation communities, which are subdivided further into 55 subcategories based largely on soil and moisture, 48

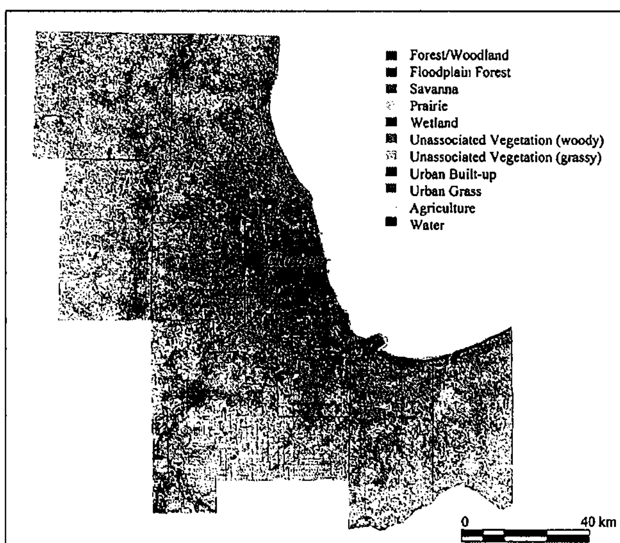


Figure 1. Land-cover map of Chicago Wilderness derived from classification of the October 1997 Landsat thematic mapper image.

Table 1. Vegetation communities in Chicago Wilderness, a classification system developed by Chicago Wilderness.

Community classes (8)	*Communities (24)*	*Subcategories (55)*
Forested communities	upland forest	dry mesic, mesic, wet mesic
	floodplain forest	wet mesic, wet
	flatwoods	northern, sand
	woodland	dry mesic, mesic, wet mesic
Savanna communities	fine-textured-soil savanna	dry mesic, mesic, wet mesic
	sand savanna	dry, dry mesic
Shrubland communities	fine-textured-soil shrubland	dry mesic, wet mesic
	sand shrubland	dry mesic, wet mesic
Prairies	fine-textured-soil prairie	dry, mesic, wet
	sand prairie	dry, mesic, wet
	gravel prairie	dry, mesic
	dolomite prairie	dry, mesic, wet
Wetland communities	marsh	basin, streamside
	bog	graminoid, low shrub, forested
	fen	calcareous floating mat, graminoid, forested
	sedge meadow	
	panne	
	seeps and springs	neutral, calcareous, acid
Cliff communities	cliff	eroding bluff, dolomite cliff
Lakeshore communities	lakeshore	beach, foredune, high dune
Cultural (human-dominated) vegetation communities	cropland	
	unassociated growth	grass, forb, shrub, tree
	tree plantation	
	developed land	

natural and 7 cultural (Table 1). Our original intent was to detect as many of the 55 subcategories as possible.

Initially, we defined nearly 150 training signatures corresponding to the different subcategories. After performing the classification, regional land managers and ecologists verified the results and refined the training signatures as needed to improve the classification accuracy. The Landsat TM data, with spatial resolution of approximately 30 m, could not reliably differentiate among similar community subcategories. To maintain a high level of accuracy at the regional scale, we collapsed the subdivisions and identified only the higher community classes. At this level, we were not able reliably to identify three community classes of cliff, lakeshore, and shrubland. At the 30-m TM resolution, we could not identify the microsystems in the vertical cliffs. For lakeshore, we identified foredunes and high dunes at the county level. We were not able to find good signatures for shrubland because these were inevitably confused with unassociated woody vegetation.

To improve the classification performance, we relied on spatial information, such as GIS soil and wetland data, from other sources. We conducted postclassification GIS modeling to identify (1) critical cultural vegetation communities, (2) wetland communities, and (3) floodplain forests.

For cultural communities, we focused specifically on two degraded types in desperate need of restoration: unassociated woody and unassociated grassy vegetation. These low-grade communities have lost their defining characteristics because of recent land-use practices and interruption of critical ecological processes such as fire and hydrology. Unassociated woody vegetation is a mixture of shrubs and trees that do not occur together naturally, either historically or as associates in self-perpetuating communities. These woody patches develop when invasive plants take over fire-starved woodlands and savannas, cut-over forests, unmanaged prairies and sedge meadows, and abandoned farm fields or Eurasian meadows. Unassociated grassy vegetation is mostly old fields dominated by Eurasian cool-season grasses. The other

Table 2. Area (ha) protected in the Illinois counties of Chicago Wilderness.

	County						
Natural community	*Cook*	*DuPage*	*Kane*	*Lake*	*McHenry*	*Will*	*Total*
Upland forest/woodland	4,928	1,484	299	874	289	1,909	9,784
Floodplain forest	2,301	387	238	711	274	834	4,746
Savanna, open oak woodland	2,360	691	234	1,249	344	652	5,529
Prairie	2,190	805	64	893	108	1,574	5,634
Wetland	2,231	1,310	443	3,362	1,947	1,447	10,735
Unassociated vegetation (woody)	4,698	717	212	103	369	981	7,081
Unassociated vegetation (grassy)	4,756	2,923	1,086	1,800	1,085	6,030	17,689

Table 3. Confusion matrix of classification for 1985 Landsat thematic mapper data.

Referenced data	Natural area	Unassociated vegetation	Agriculture	Urban land	Row total	Omission error (%)	Accuracy (%)
	Classified data						
Natural area	201	6		1	208	3.36	96.6
Unassociated vegetation		40			40	0	100
Agriculture			52	6	58	10.34	89.7
Urban land	7	8		100	115	13.04	86.9
Column total	208	54	52	107	421		
Commission error (%)	3.4	25.9	0	6.5			overall 93.4

two focal cultural communities are developed land and cropland. Developed land (urban built-up and urban grass in Fig. 1) includes all lands dominated by human structures, including strip mines, buildings, cemeteries, roadways, and urban grasses. Cropland (agriculture in Fig. 1) is row and forage crops.

Identification of the wetland communities from the 1997 October Landsat TM image was hampered by the extreme dryness of that autumn. Desiccated wetlands have a reflectance and spatial pattern similar to those of bare-soil farmland and unassociated grassy vegetation. Wetland communities therefore were misclassified as cropland and unassociated vegetation. To address this problem, we referenced the TM image data to wetland maps developed by the Illinois Department of Natural Resources (Illinois Department of Natural Resources 1996) and used GIS masking to identify the wetlands. The wetland communities identifiable by Landsat were primarily basin and streamside marshes and sedge meadows. Bogs, fens, and pannes were too small for detection.

To identify floodplain forests, which are characterized by periodic flooding, we processed Landsat TM images acquired on 28 April and 30 May 1995. The 28 April image coincided with the time of peak discharge of the major rivers in the Chicago area, when most of the floodplain forests were inundated. The 30 May 1995 image, on the other hand, depicts normal water levels. The short interval between the two images assures that most differences noted either depict phenological changes or are related to flooding. After classification of both 1995 images, we used Boolean-logic GIS modeling to identify the floodplain forests. Pixels that were labeled water (flooded) in the April image and forest/woodland in the May image were characterized as floodplain forest.

From Fig. 1 we developed vegetation maps of the region and delineated lands owned and protected by municipal units (county forest preserves and conservation districts) and federal and state agencies. Table 2 shows the surface areas of natural communities (including unassociated vegetation) within protected reserves. These banks of geographically referenced data make possible the quantitative tracking of regional trends over time.

An important result of the land-cover map is the characterization of vegetation outside preserves. Further refinement of the data is necessary to get reliable totals for surface area, but even qualitative profiles of the matrix surrounding protected areas can indicate critical areas for acquisition or restoration by land managers.

Analysis of Land-Cover Change

To assure the greatest accuracy in analyzing land-cover change, we recoded the classified Landsat data into five categories only: (1) urban land (developed land in Table 1); (2) natural area (forested, savanna, shrubland, prairie, and wetland communities in Table 1); (3) unassociated vegetation (unassociated growth in Table 1); (4) agriculture (cropland in Table 1); and (5) open water.

Table 4. Confusion matrix of classification for 1997 Landsat thematic mapper data.

Referenced data	Natural area	Unassociated vegetation	Agriculture	Urban land	Row total	Omission error (%)	Accuracy (%)
	Classified data						
Natural area	248	6	3	1	258	3.88	96.1
Unassociated vegetation		53	2	2	57	7.02	93
Agriculture	1	1	60		62	3.23	96.8
Urban land	2	8	3	92	105	12.38	87.6
Column total	251	68	68	95	482		
Commission error (%)	2.0	22.0	11.8	4.2			overall 94.0

Table 5. Confusion matrix of classification for 1972 Landsat multispectral scanner data.

	Classified data						
Referenced data	*Natural area*	*Unassociated vegetation*	*Agriculture*	*Urban land*	*Row total*	*Omission error (%)*	*Accuracy (%)*
Natural area	207	5	6	3	221	6.76	93.7
Unassociated vegetation	5	33	4	2	44	33.32	75.0
Agriculture	2	2	55	3	62	12.73	88.7
Urban land	1	6	5	82	94	14.63	87.2
Column total	215	46	70	90	421		
Commission error (%)	3.7	28.3	21.4	8.9			overall 89.6

Assessments of the land-cover classification indicate high overall accuracy (approximately 93%) for the generalized 1985 and 1997 data (Tables 3 & 4). Because of the different spatial resolution for the 1972 Landsat MSS data (at 80 m), these data were resampled to conform to the spatial resolution of the 30-m TM data. The results were not as accurate (Table 5).

Dramatic increases in urban land dominate the land-cover changes detected between 1972, 1985, and 1997 (Fig. 2). Between 1972 and 1985, urban land increased by 14.5% (Table 5). This increase in urban and suburban sprawl accelerated to nearly 30% between 1985 and 1997. Between 1972 and 1997, the extent of developed land increased 49%. Most of the suburban land expansion came at the expense of agricultural lands, with a total decrease of 37% over the 25 years. Yet more than one-fifth of the natural area (21%, or 47,986 ha) (Table 6) was converted to urban use during that period.

Another significant change in land cover is the increase in unassociated vegetation over time (Table 6). This increase reflects (1) degradation of natural lands in the absence of appropriate management and ecological restoration and (2) abandoned agricultural fields. But the increase in unassociated vegetation shown between 1972 and 1985 probably is inflated: coarser spatial resolution of the 1972 MSS data and lack of ground truthing made identification of this category difficult.

Table 7 summarizes the changes in land cover between 1985 and 1997 that were detected in the counties surrounding and encompassing downtown Chicago. To calculate the pattern of change based on distance from the city, we divided the area into five concentric zones of 0–15 km (zone I), 15–30 km (zone II), 30–45 km (zone III), 45–65 km (zone IV), and more than 65 km (zone V) from the center of downtown Chicago. We compared the proportion of land converted to urban use in the different zones by calculating both the percent increase in urban land since 1985 and the density of change (i.e., hectares of land converted to urban land per square kilometer) for each zone. Zone III, the area that showed the most intense density change (11 ha/km^2), was also the zone with most forest preserves and natural lands (Fig. 1). The increase in urban land cover in Zone IV was almost 80% over this 12-year period.

Rampant urban sprawl results not only in wholesale loss of natural (and degraded) lands, but also in extreme fragmentation and isolation of the remaining natural areas within the suburban matrix. In a closeup view of Naperville (Fig. 3), a suburb west of Chicago, most of what was agriculture (yellow) in 1985 had become urban structures (red) 12 years later. The increase in urban land (2472 ha) was a 234% expansion from 1985 (1054 ha). Spring Brook Prairie Preserve, a 688-ha prairie and wetland restoration site, is represented by the large green rectangle in the lower center of the top two images in Figure 3. At the start of restoration in 1973, the site was in the midst of agricultural fields. Twelve years later, in 1985, the preserve was still surrounded primarily by agriculture. But the following 12 years transformed the preserve into an island in a sea of subdivisions and commercial centers.

Discussion

Our aims in this change-detection project were ambitious in terms of remote sensing and GIS technology,

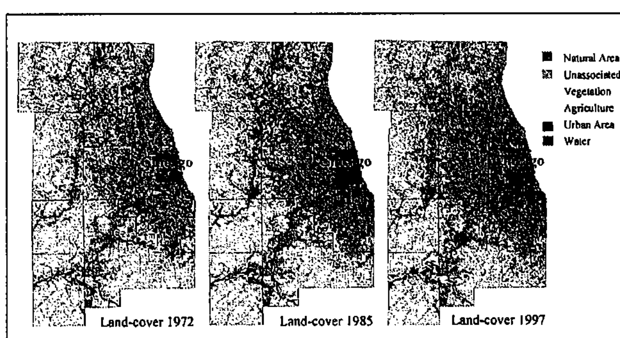


Figure 2. Land-cover map of the Illinois counties of Chicago Wilderness in 1972, 1985, and 1997.

Table 6. Changes in land cover between 1972 and 1997 (in hectares).

Category	Land cover 1972	Land cover 1985	Land cover 1997	Change in land cover (% change)* 1972-1985	1985-1997	1972-1997
Urban land	227,487	260,498	338,612	+ 33,011 (15)	+ 78,114 (30)	+ 111,125 (49)
Natural area	227,047	209,796	179,061	− 17,251 (08)	− 30,735 (15)	− 47,986 (21)
Agriculture	599,462	468,804	375,537	− 130,658 (22)	− 93,267 (20)	− 223,925 (37)
Unassociated vegetation	80,644	199,355	244,716	+ 118,711 (147)	+ 45,361 (23)	+ 164,072 (203)

Symbols: +, increase; −, decrease in land cover in category.

geographic and institutional scope, and direct application to conservation decisions. We sought to create a vegetation map of Chicago Wilderness, to examine changes in land use and cover, and to integrate satellite data with planning.

Vegetation Map of Chicago Wilderness

The vegetation map of Chicago Wilderness was created for use in the development of the biodiversity recovery plan for the region. The resulting maps and the baseline map of land cover from which they were derived already are serving as benchmarks against which we can measure progress toward the landscape-level goals of the recovery plan. This project also was the catalyst for development of the Chicago Wilderness system of community classification (Table 1). Following this classification system, ecologists at a series of Chicago Wilderness workshops set conservation priorities for community types according to their global and regional status, importance, and distribution (Chicago Wilderness 1999). In the process, they also identified the ranked conservation targets toward which visions, goals, and strategies for regional recovery should be directed.

The scope of satellite imagery and the flexibility of GIS-generated visual tools (the base maps) can be manipulated manually for use in goal setting, management, and monitoring. They also can be used to generate digitized layers of information (for example, the size and distribution of protected areas) that can be displayed and analyzed separately. The set of images in Fig. 4 reveals how patches of single cover types are spread across the landscape. Clearly visible is the fragmentation of all remnant natural communities. This series also underscores the extent of unassociated vegetation—a symptom of ecological decline, and a sign of the potential for widespread restoration.

At the regional scale, we were unable to detect community types at hierarchical levels as fine as we had hoped for at the outset of the project. County by county, however, we may be able to push resolution to more detail, enabling land managers to set landscape-level goals at the local scale. Even at the coarser regional scale of resolution, the magnitude of the most serious threats is apparent.

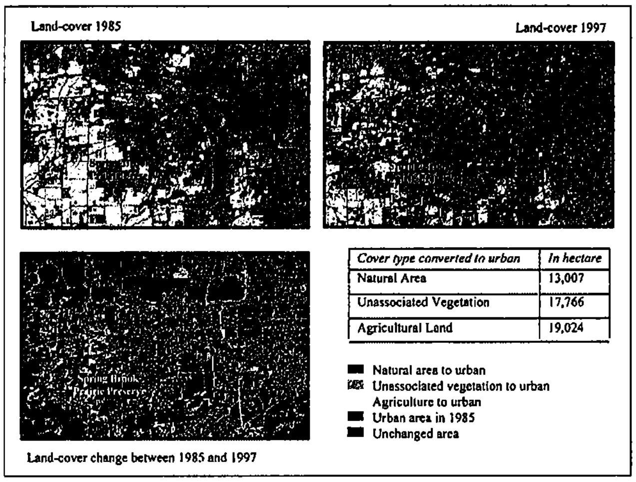
Change in Land Use and Land Cover

We examined changes in land use and land cover over the past 25 years to highlight the most severe threats to the region's globally important natural remnants. The 25-year horizon and the three temporal "slices" within it revealed dramatic trends in land use commensurate with the coarser scale of regional resolution. Qualitative comparisons such as in the Naperville close-up (Fig. 3) are strong evidence that wholesale conversion is not the only landscape-level process threatening the natural communities of Chicago Wilderness. Fragmentation, isolation, and the quality of the matrix in which natural lands

Table 7. Changes in land cover between 1985 and 1997 as a measure of distance from downtown Chicago.

Distance from downtown Chicago*	Natural area to urban (ha)	Unassociated vegetation to urban (ha)	Agriculture to urban (ha)	Total converted to urban (ha)	Urban in 1985 (ha)	Increase in urban land cover (%)	Density of change (ha/km^2)
Zone I (474 km^2)	329	295	149	773	38,059	2.03	1.63
Zone II (1188 km^2)	3,559	3,232	1,335	8,126	48,037	16.92	6.84
Zone III (1769 km^2)	5,505	7,479	7,428	20,412	32,917	62.01	11.54
Zone IV (3133 km^2)	5,049	7,663	10,044	22,756	29,898	76.11	7.26
Zone V (3140 km^2)	1,739	4,896	6,035	12,670	23,992	52.81	4.04

Zone I, 0-15 km; II, 15-30 km; III, 30-45 km; IV, 45-65 km; and V, >65 km from the center of downtown Chicago.



Cover type converted to urban	In hectare
Natural Area	13,007
Unassociated Vegetation	17,766
Agricultural Land	19,024

Figure 3. Close-up view of land-cover change between 1985 and 1997 in Naperville, a western suburb of Chicago. For key to colors in top two maps, see Fig. 2

are embedded can be equally important (e.g., land-use changes around Spring Brook Prairie Preserve).

Quantitative comparison was particularly telling in the case of one of the most severe threats to regional biodiversity; urban and suburban sprawl. Poorly planned development contributed more heavily to ecological degradation than did sheer population growth. Between 1970 and 1990, the surface area of metropolitan Chicago's developed land increased by 49%, whereas its population grew by only 4%. The Northeastern Illinois Planning Commission projects that the region's population will increase by 25% over the next 25 years. At current rates, the accompanying conversion of open land would be catastrophic. Combined with the visual power of the land-cover maps, the quantitative results of the change-detection project dramatically illustrate the need for reform of land-use policies.

Circumstance limited our ability to map and quantify some other pervasive regional threats. For example, aggressive exotic plant species threaten almost every community type in Chicago Wilderness (Chicago Wilderness 1999). Buckthorn (*Rhamnus*) is an exotic invasive shrub that holds its leaves into late fall, long after native species have lost theirs. Satellite images taken in November likely would have shown us the extent of this threat in the region, but in 25 years not one November image has been cloud-free. Dry conditions in wetlands during 1997 prevented us from detecting the extent of the spread of aggressive purple loosestrife (*Lythrum salicaria*). Acquisition and analysis of future images may provide us with missing information. Despite weaknesses, the baseline data create a georeferenced framework for field reconnaissance of these threats and others.

Maps such as Fig. 4 show not only risks but also opportunities for conservation. Seen in this light, the constellation of unassociated growth can be a map for ecological restoration. Patches of woodland can be anchors for reconnection through corridors and greenways.

Integrating Satellite Data and Planning

Our final goal was to integrate the vegetation map and data into the recovery plan and into the GIS database for Chicago Wilderness. Chicago Wilderness is founded on partnership. And the regional change-detection project funded by NASA provided a forum for collaboration among a broad suite of conservationists. Land managers with expert knowledge of ecosystems on the ground, scientists with skills in remote sensing and GIS, and planners with experience in the urban environment cooperated across geography and across institutions. The availability of the database to Chicago Wilderness members and others is a vehicle for the long-term persistence of this action-oriented partnership.

Our work could be an organizing point around which a regional conservation constituency could grow. By presenting complex concepts from the recovery plan in accessible, striking visual form, the land-cover maps and quantitative measures of change could be a call to action for the public of Chicago Wilderness.

Erosion of the Chicago region's globally important biodiversity results not only from large-scale policy decisions but also from the day-to-day activities of millions of households and businesses. Strong, clear images of change

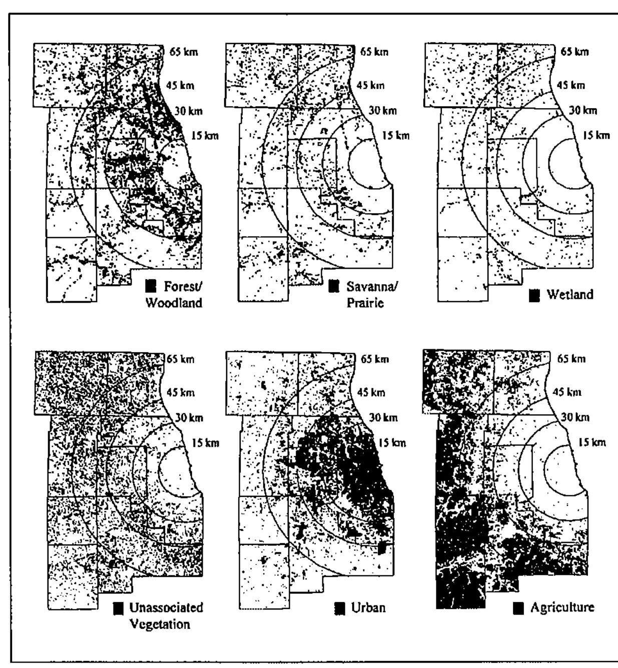


Figure 4. Patches of single cover types across the Chicago Wilderness landscape (1997).

in land use can motivate change in individual and group conservation behavior, from consumption habits to voting patterns. Such a transformation of regional culture is an ultimate goal of Chicago Wilderness.

Acknowledgments

This project was the coordinated effort of an enormous group of ecologists, land managers, and geographic information system (GIS) experts in the region. We thank all of them, in particular land managers and ecologists J. Anderson, N. Pavlovic, W. Schennum, D. Short, J. Siddens, L. Stritch, S. Thomas, and D. Ullberg for their countless revisions and refinements of the land-cover maps. County GIS specialists L. Berns and L. Sasamoto contributed data and analyses. Regional ecologists S. Packard, W. Lampa, J. Steffen, S. Thomas, and other members of the Chicago Wilderness Science and Land Management Teams participated with advice, fieldwork, and development of the regional classification scheme. W. Lampa, L. Masters, and coworkers undertook most of the ground truthing. We also thank J. Anderson for her contributions. X. Zhang helped in GIS data processing and landscape characterization. For gathering global position system data and analyzing GIS data we thank R. Harari-Kremer, M. E. Ward, H. Liu, and J. T. Anderson. T. Sullivan, S. Packard, E. McCance, and K. Fuller represented a critical link to the Regional Biodiversity Recovery Plan. W. Turner and A. Janetos of the National Aeronautics and Space Administration (NASA) provided constant support throughout the project. For countless revisions and editing of drafts we thank J. Shopland. Three anonymous reviewers and E. Main contributed to the final manuscript. This project was funded by NASA grant GP37J under the project "Tracking Natural Community Fragmentation and Changes in Land Use and Land Cover: A Case Study of Chicago Wilderness" and NASA New Investigator Program (NIP) in Earth Science grant NAG5-8829.

Literature Cited

Baker, W. L., and Y. Cai. 1992. The programs for multiscale analysis of landscape structure using the GRASS geographic information system. Landscape Ecology 7:291-302.

Campbell, J. B. 1997. Introduction to remote sensing. Guilford Press, New York.

Chicago Wilderness 1999. Biodiversity recovery plan. Chicago Wilderness, Chicago.

Colwell, R. N., editor. 1983. Manual of remote sensing. 2nd edition. American Society of Photogrammetry, Falls Church, Virginia.

Holz, R. K. 1985. The surveillant science: remote sensing of the environment. 2nd edition. Wiley, New York.

Illinois Department of Natural Resources. 1996. Illinois land cover, an atlas. IDNR/EEA-96/05. Illinois Department of Natural Resources, Springfield.

Jensen, J. R. 1996. Introductory digital image processing: a remote sensing perspective. Prentice-Hall, Upper Saddle River, New Jersey.

Lo, C. P. 1986. Applied remote sensing. Longman, New York.

Olsen, E. R., R. D. Ramsey, and D. S. Winn. 1993. A modified fractal dimension as a measure of landscape diversity. Photogrammetric Engineering and Remote Sensing 59:1517-1520.

O'Neill, R. V., J. R. Krummel, R. H. Gardner, G. Sugihara, B. Jackson, D. L. DeAngelis, B. T. Milne, M. G. Turner, B. Zygmunt, S. W. Christensen, V. H. Dale, and R. L. Graham. 1988. Indices of landscape patterns. Landscape Ecology 1:153-162.

Quattrochi, D. A., and R. E. Pelletier. 1991. Remote sensing for analysis of landscapes: an introduction. Pages 51-76 in M. G. Turner and R. H. Gardner, editors. Quantitative methods in landscape ecology. Springer-Verlag, New York.

Reeves, R. G., editor. 1975. Manual of remote sensing. American Society of Photogrammetry, Falls Church, Virginia.

Ritters, K. H., R. V. O'Neill, C. T. Hunsaker, J. D. Wickham, D. H. Yankee, S. P. Timmins, K. B. Jones, and B. L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecology 10:23-39.

Turner, M. G. 1990. Spatial and temporal analysis of landscape patterns. Landscape Ecology 4:21-30.

Turner, S. J., R. V. O'Neill, W. Conley, M. R. Conley, and H. C. Humphries. 1990. Pattern and scale: statistics for landscape ecology. Pages 19-49 in M. G. Turner and R. H. Gardner, editors. Quantitative methods in landscape ecology. Springer-Verlag, New York.