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Factors and Processes Shaping Land Cover and Land Cover Changes Along the Wisconsin River

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Abstract

Land use can exert a powerful influence on ecological systems, yet our understanding of the natural and social factors that influence land use and land-cover change is incomplete. We studied land-cover change in an area of about 8800 km^2 along the lower part of the Wisconsin River, a landscape largely dominated by agriculture. Our goals were (a) to quantify changes in land cover between 1938 and 1992, (b) to evaluate the influence of abiotic and socioeconomic variables on land cover in 1938 and 1992, and (c) to characterize the major processes of land-cover change between these two points in time. The results showed a general shift from agricultural land to forest. Cropland declined from covering 44% to 32% of the study area, while forests and grassland both increased (from 32% to 38% and from 10% to 14% respectively). Multiple linear regressions using three abiotic and two socioeconomic variables captured 6% to 36% of the variation in land-cover categories in 1938 and 9% to 46% of the variation in 1992. Including socioeconomic variables always increased model performance. Agricultural abandonment and a general decline in farming intensity were the most important processes of land-cover change among the processes considered. Areas characterized by the different processes of land-cover change differed in the abiotic and socioeconomic variables that had explanatory power and can be distinguished spatially. Understanding the dynamics of landscapes dominated by human impacts requires methods to incorporate socioeconomic variables and anthropogenic processes in the analyses. Our method of hypothesizing and testing major anthropogenic processes may be a useful tool for studying the dynamics of cultural landscapes.

Key words: land-use history; land-cover change; landscape ecology; driving forces; Wisconsin River; floodplain; Upper Midwest.

Introduction

The abiotic template is a powerful constraint on the patterns that develop in landscapes and the manner in which these patterns change through time. Analyzing changes in cultural landscapes requires considering, and if possible quantifying, the human impact (Lee and others 1992; Riebsame and others 1994; Turner and others 1996; Wear and Bolstad 1998; Dale and others 2000; Riera and others 2001). In some regions, land-use changes appear to be closely related to the physical attributes of the landscape (for example, see Pan and others 1990, but also see Paquette and Domon 1997; Silbernagel and others 1997); in other regions, land-use patterns appear to be poorly correlated with such characteristics (for example, see Iverson 1988). The connection between landscape patterns and environmental conditions may be weakened if human activities remove or reduce some of the constraints set by the abiotic template (for example, see Mladenoff and others 1993; White and Mladenoff 1994); intensification of agriculture, for example, may do this by eliminating the constraints of water (either

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excess or lack) or nutrient availability. Eliminating the constraints of one abiotic variable might also increase the importance of other abiotic factors (for example, see Auclair 1976).

The Upper Midwest (USA), settled by Europeans in the mid to late 1800s, is characterized today by large areas of intensive agriculture. Farming in the United States underwent rapid and far-reaching changes during the 20th century. The increasing availability of fossil fuels triggered greater mechanization and increased the availability of fertilizers and pesticides. As a consequence, farming became more capital intensive (Dorner 1981) and the average farm became larger (Olmstead 1997).

In this study, we examined factors and processes shaping land cover and land-cover changes in the Upper Midwest. Our goals were (a) to quantify changes in land cover in 1938 and 1992, (b) to evaluate the influence of abiotic and socioeconomic variables on land cover in 1938 and 1992, and (c) to characterize the major processes of land-cover changes between these two points in time. The study area has been largely an agricultural landscape throughout the 20th century, with changes in and from agriculture dominating land-use change. We hypothesized that agriculture became increasingly restricted to more favorable soil conditions, reflecting a tendency to abandon farms on poorer soils. We therefore expected the most important processes driving land-cover change to be the intensification of farming on favorable soils and the abandonment of farming on poorer soils. We developed a conceptual model, which allows testing the plausibility of hypothesized processes driving land-cover change with respect to abiotic and socioeconomic variables.

The Landscape of the Lower Wisconsin River

Land-use and land-cover patterns in areas near surface waters have a significant impact on water quality (for example, see Jordan and others 1993, 1997; Naiman and others 1995; Naiman 1996; Carpenter and others 1998; Wear and others 1998). The watershed of the Wisconsin River has been highly modified by agriculture and urban development, which has fragmented both wetlands and floodplain forests, and it is similar to riverine landscapes throughout the Midwest. We studied a corridor of approximately 20 km width along the lower 380 km of the Wisconsin River (Figure 1). The 8800-km^2 study area includes 3403 sections, the one-square-mile grid cell of land surveys for many regions of the United States (Johnson 1976).

The landscape of the Upper Midwest includes both glaciated and unglaciated parts; the latter is called "the Driftless Area" (Martin 1965). The Wisconsin glaciation left a gently rolling terrain in areas directly covered by ice and a more rugged terrain of ridges and valleys in the Driftless Area. Our study area includes four major ecological units (NHFEU, WDNR 1999): the Farm–Forest Transition (FFT), the Central Sand Plains (CSP), the southern part of the Central Sand Hills (CSH), and the Western Coulees and Ridges (WCR) (Figure 1). The geomorphologic features of those ecoregions are in different ways related to the imprints of Wisconsin glaciation on the landscape. The FFT and CSH regions were both glaciated and are separated by the CSP, which is characterized by sand deposited in the former Glacial Lake Wisconsin (Martin 1965). These sandy deposits created conditions for agriculture that are distinctly different from other parts of the region, setting the scene for Aldo Leopold's *Sand County Almanac* (Leopold 1949). The WCR region occurs in the Driftless Area. Whereas many glaciated landscapes have naturally productive soils due to the silt produced by the erosive forces of the glacier, the soils of the unglaciated Driftless Area also benefited from glaciation as windblown silt, called "loess," was blown in and formed fertile soils.

In the FFT region (Figure 1), the vegetation before Euro-American settlement consisted of northern mesic forests dominated by maple (*Acer sp.*), hemlock (*Tsuga canadensis*), and yellow birch (*Betula lutea*) (Cottam and Loucks 1965). The sandy lake deposits in the CSP region were covered with pine barrens dominated by jack pine (*Pinus banksiana*) and prairie grasses (Cottam and Loucks 1965). Areas of the study region falling in the CSH and WCR regions generally belong to the southern-hardwood forest, with prairie and oak savannas dominated by bur oak (*Quercus macrocarpa*) (Curtis 1959). Adjacent to the river, species-rich lowland forests were common and included river birch (*Betula nigra*), smooth buckeye (*Aesculus glabra*), honey locust (*Gleditsia triacanthos*), sycamore (*Platanus occidentalis*), black willow (*Salix nigra*), cottonwood (*Populus deltoides*), white oak (*Quercus bicolor*), silver maple (*Acer saccharinum*), and American elm (*Ulmus americana*).

Settlers moved into the region in the mid 19th century, advancing from southeast to northwest (Ostergren 1997). After a period of lead mining and the production of wheat, which was successfully exported until the early 1870s, southwestern Wisconsin changed to a dairying region, with a focus on cheese (Conzen 1997). Population densities in the counties along the Wisconsin River rose during the

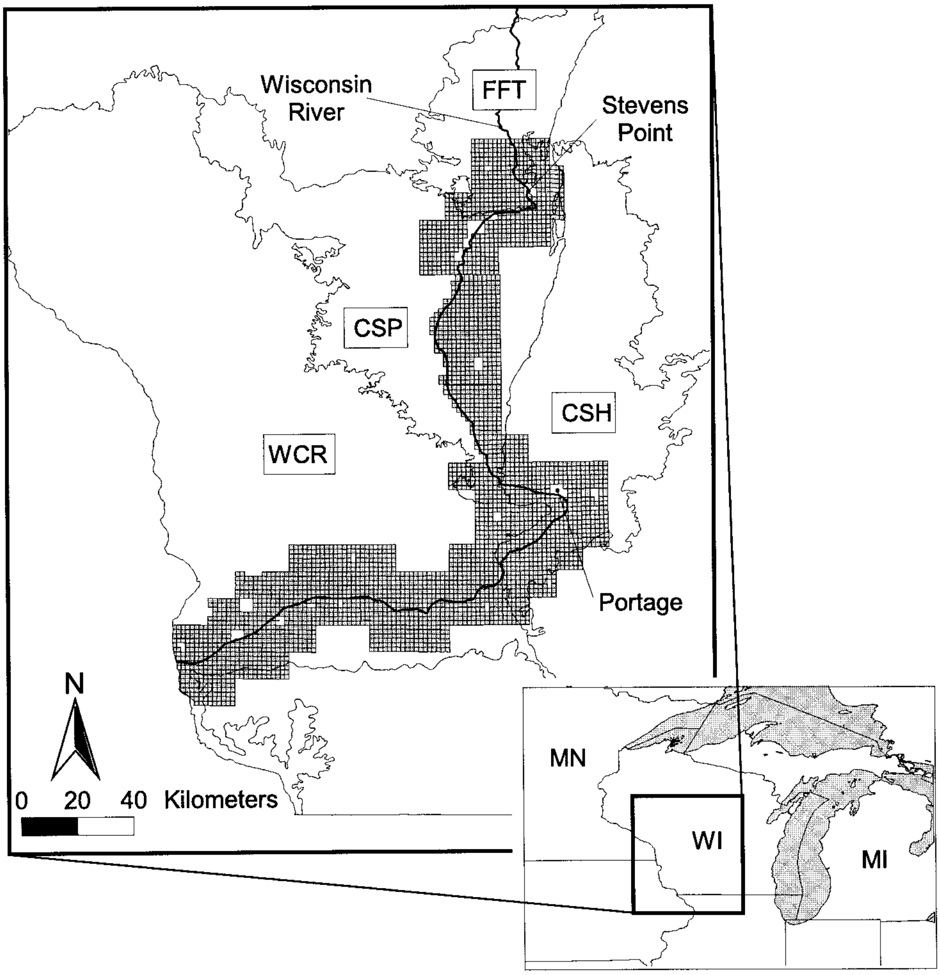

Figure 1. Map of study area along the Wisconsin River, Wisconsin, USA. FFT = Farm–Forest Transition, CSP = Central Sand Plains, CSH = Southern part of the Central Sand Hills, WCR = Western Coulees and Ridges.

19th century, then remained fairly stable during the first decades of the 20th century (Figure 2a). For 1940 and 1990, population density data are available for the towns comprising the study area itself. The close match of these values (crosses in Figure 2a) with the timeline compiled at the county level suggests that changes in the study area are well represented by the changes in the respective counties. Thus, the proportion of the land that is part of farms compiled on the county level (Figure 2b) very likely also represents the development within the study area. The increase in population during the 19th century was paralleled by an increase in active farmland, which also leveled off during the first decades of the 20th century. Since the 1940s, the proportion of land in farms decreased slightly but steadily as population density continued to increase. The changes visible in Figure 2 reveal that the study period selected (1938–92) covers an era of increase in population and decrease in farming after a relatively stable period in the first decades of the century. Only minor changes occurred in the proportion of land in farms (Figure 2b) during the study period. The smooth curve also indicates a small year-to-year variability in land cover—a prerequisite for our study of land-cover changes based on two instantaneous surveys in 1938 and 1992.

The settlers profoundly changed the original land cover of forests, savanna, and prairie (Auclair 1976; Tans 1976; Lange 1990) through land use and fire suppression (for example, see Kline and Cottam 1979; Dorney 1981). Land-use and land-cover changes affected both uplands and floodplain forests. Today, large floodplain forests are considered a threatened ecosystem (Yin and others 1997; Knutson and Klaas 1998). Changes on these floodplains (for example, see Barnes 1997) and the surrounding uplands (for example, see Auclair 1976) can only be understood in the wider context of regional land-use and land-cover change.

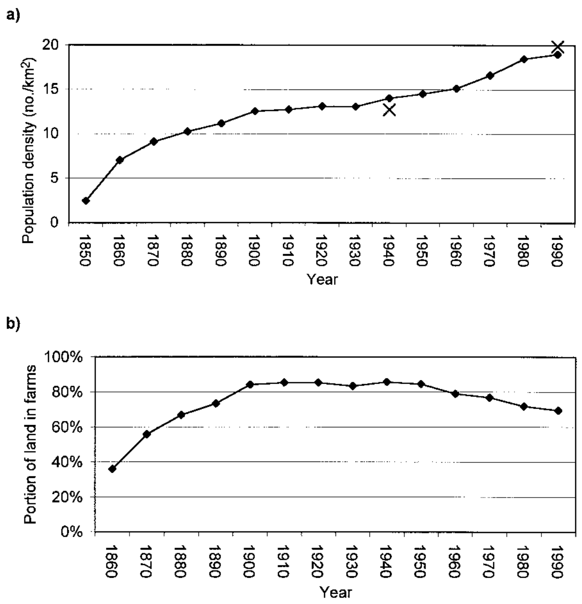

Figure 2. Change in (a) population density and (b) portion of the land in farms in the counties comprising the study area. Crosses in a indicate population densities for the towns comprising the study area at the specific dates examined (US Census Bureau 1940, US Census Bureau 1990).

Materials and Methods

Land-cover Data, 1938

Land-cover data for 1938 were obtained from the Wisconsin Land Economic Inventory (State of Wisconsin 1936), also known as "the Bordner Report," in which Wisconsin's land cover was mapped by trained field workers crossing the land at intervals of a quarter mile (about 400 m) and covering the whole area (State of Wisconsin 1936). As a unique source of information prior to marked mechanization and intensification of crop production, these maps have been widely used (for example, see Auclair 1976; Mladenoff and Howell 1980; Lange 1990). We compiled data from unpublished tables (Archive of the State Historical Society of Wisconsin, Series 1956) containing summarized acreage of the different land-cover types (Table 1) for all 3403 sections. No such tables are available for Juneau County, located in the Central Sand Plains on the western side of the Wisconsin River. Juneau County is therefore excluded from the study area (Figure 1). Sections were the spatial entity within which all other spatial information was compiled or summarized.

Land-cover Data, 1992

Land-cover data for 1992 were compiled from the Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND) database. WISCLAND includes land-cover maps derived from 1992 Landsat TM imagery produced by the Environmental Remote Sensing Center of the University of Wisconsin (Lillesand and others 1998). The TM data are based on a pixel size of 30 m^2, and the resulting land-cover map was verified with extensive ground proofing (more information on WISCLAND can be found at http://www.dnr.state.wi.us/org/at/et/geo/data/wlc.htm).

Classification of Land-cover Data

We classified the land-cover data for 1938 and 1992 into nested categories applicable to both data sets (primary and secondary categories in Table 1). Land cover in both maps was expressed as the proportion of each cover type by section and therefore does not give the areas covered by one cover type. Agricultural land, forests, and wetlands were selected as primary categories. Agricultural land includes cropland and grassland as secondary categories. Forests include the secondary categories of deciduous forests, coniferous forests, and mixed forests. Wetlands include the secondary categories of forested wetland, shrubby wetland, and open wetland. Sections that were mostly urban in 1938 were excluded from the analyses and are blank in our maps (for example, Figure 1) because they were not surveyed in the Wisconsin Economic Land Inventory.

Abiotic Variables

The data used are all easily available (Table 2), which makes our approach more applicable to other regions. Within the study area, little variation in climatic factors, such as mean annual temperature and precipitation, can be detected (Martin 1965). The major topographical feature is the distinction between the floodplain area and the surrounding uplands. Because those two areas also show distinct differences in soil characteristics, we did not include topography as an additional variable. The extent of the study region allowed us to use the State Soil Geographic Database STATSGO (Soil Conservation Service 1995) to develop soil coverages. STATSGO was based on generalized soil survey maps and can be used on a regional level.

Surface texture was characterized as the portion of a soil mapping unit dominated by sand, loam, and silt (Table 2). We summarized areas of sand, loamy sand, fine sand, and loamy fine sand to get the percentage covered by sandy soils. Similarly, we

Table 1. Land-cover Variables as Given in the Surveys and Categories Created for the Comparison

Primary Categories	Secondary Categories	Categories Used in the Wisconsin Economic Inventory (1938)	Categories Used in WISCLAND (1992)
Agricultural land	Cropland	cleared, poor land previously cropped, erosion, cultivated stumps, nurseries, orchards & vineyards	agriculture—herbaceous/field crops—com agriculture—herbaceous/field crops—other row crops agriculture—herbaceous/field crops—forage crops: includes hay and hay/mix
	Grassland	pasture, permanent pasture, abandoned land, stump pasture	agriculture—grassland—grassland: includes timothy, rye, pasture, idle, CRP, grass, and volunteer
Forest	Deciduous forest	oak hickory type (southern), mixed upland hardwoods, scrub oak with some red maple, popple with some white birch, oak hickory type (southern), upland brush (pin cherry, willow, hazel, etc.), white birch	forest—broad leaved deciduous—oak forest—broad-leaved deciduous—maple forest—broad-leaved deciduous—mixed/other broad-leaved deciduous shrubland
	Coniferous forest	jack pine, white pine, black spruce, Norway pine, forest plantation	forest—coniferous—jack pine forest—coniferous—red pine forest—coniferous—mixed/other coniferous
	Mixed forest	hardwood with some conifers, hemlock with hardwoods	forest—mixed deciduous/coniferous
Wetland	Open wetland	grass marsh, sedge marsh, sedge hay marsh, cat tail, weedy peat, leather leave	wetland—emergent/wet meadow
	Shrubby wetland	tagalder, willow	wetland—lowland shrub—broad-leaved deciduous wetland—lowland shrub—broad-leaved evergreen wetland—lowland shrub—needle-leaved
	Forested wetland	swamp hardwoods, tamarack, white cedar	wetland—forested—broad-leaved deciduous wetland—forested—coniferous wetland—forested—mixed deciduous/coniferous
Other	Other	slash, recent burn, golf ground, water, cranberry, open, gravel pits, cities, junkyard public dump, airports, urban parks, cementery, fairground, governement land, CCC camp, radio transmission station	urban/developed—golf course water agriculture—cranberry bog barren urban/developed—high-intensity urban/developed—low-intensity

Table 2. Variables Used in the Regression Model

Name	Data Type	Spatial Character	Data Source
Land-cover Variables (Dependent Variables)			
Land cover 1938	Proportion of area	Section	Wisconsin Economic Land Inventory
Land cover 1992	Proportion of area	Section	WISCLAND
Change in land cover 1938–1992	Proportion of area	Section	
Abiotic Variables (Independent Variables)			
Sand	Proportion with sandy surface texture	Section	STATSGO
Loam	Proportion with loamy surface texture	Section	STATSGO
Silt	Proportion with silty surface texture	Section	STATSGO
Depth to bedrock	cm	Section	STATSGO
Available water capacity	cm	Section	STATSGO
Socioeconomic Variables (Independent Variables)			
Population density 1940	Density by town	Town	US Census Bureau 1940
Population density 1990	Density by town	Town	US Census Bureau 1990
Change in population 1940–1990	Proportional change	Town	
Farm economy 1937	Average number of tractors by farm	Town	State Historical Society, Archive. Series 755. MAD 3/19/D4-6
Farm economy 1992	Ratio of farm economy	ZIP code area	Census of Agriculture 1992
Land managed by the DNR	Proportion of area	Section	http://www.limnology.wisc.edu/spatial/sdcatalog.html

summarized loam, sandy loam, fine sandy loam, silty clay loam, flaggy-loam, and bouldery-sandy loam to obtain the area dominated by loam, and we summarized silt loam, cobbly silt loam, and stony-silt loam to get the area dominated by silt. Average depth of the soil to bedrock (that is, soil depth) and the average available water capacity (that is, the volume of water that should be available to plants if the soil, inclusive of rock fragments, were at field capacity) within a soil mapping unit were calculated in centimeters. To determine the available water capacity, we calculated weighted averages following a procedure described by the Soil Conservation Service (1995). The soil coverages were combined with the section boundaries, and area-weighted averages of the soil characteristics were computed for each section.

Socioeconomic Variables

A set of variables was chosen to characterize the spatial variability in socioeconomic conditions throughout the study region. We assumed that population density (that is, signs of suburbanization, land abandonment, and so on) and—given that the study area is largely dominated by farming—farm economic status were among the most important factors influencing land cover. Ownership status of the land was also considered, since land in public ownership is likely to experience different land-cover changes (Mladenoff and others 1993; Spies and others 1994; Turner and others 1996). Selection of proxies of socioeconomic conditions is always restricted by data availability, and it is crucial to consider the consequences of limited data availability on the results of a study.

Population densities for 1940 (US Census Bureau 1940) and 1990 (US Census Bureau 1990) were compiled per town, and the relative change between 1940 and 1990 was calculated (Table 2). The portion of a section in public ownership was calculated on a map provided by the Wisconsin Department of Natural Resources (DNR) (http://www.limnology.wisc.edu/spatial/sdcatalog.html). However, this information was only available for the 1990s.

The economic condition of farms will strongly affect land cover and its change. As proxies of farm economy, we chose two factors (Table 2). For the 1930s, we chose the average number of tractors per farm on the town level given in unpublished tables of the Wisconsin Agricultural Statistics for 1937 (Archive of the State Historical Society of Wisconsin, Summaries of Assessors' Farm Statistics by Counties: 1937/38, Series 755). Numbers of tractors per farm, ranging from 0 to 0.76 tractors per farm with a mean of 0.25, are likely to reflect farming intensity, which is correlated with the impacts on natural resources such as water and soil. For the 1990s, we used the ratio of number of farms with market value of agricultural products sold greater than $100,000 vs the number with less than $10,000 as reported for 1992 (Census of Agriculture 1992). The ratio of the two variables indicates whether the area was dominated by high-income farms or by smaller, less productive operations.

The socioeconomic variables were available at the level of the 107 towns (population, farm economic status proxy 1937) and at the level of the 53 ZIP code (postal code) areas (farm economic status proxy 1992) within the study area. For the abiotic variables, the boundaries of the units used for socioeconomic data were combined with section boundaries in a Geographic Information System (GIS), and area-weighted averages of variables were computed for each section. The large number of sections included in the analyses compensates for the fact that units of analysis are smaller than those for which they were reported.

Land-cover Analysis

The relationship between land cover for 1938 and 1992 and the abiotic and socioeconomic variables was analyzed using multiple linear regression (SAS Institute 1990). Prior to the regression, land-cover data were transformed [arcsine (square root (land cover)); Zar 1984] as they are proportions of a given section. Models were chosen using a stepwise selection, with a threshold of $P \leq 0.05$ for retention in the model. Explanatory power was assessed using the coefficient of determination, R^2. Prior to regression, univariate Pearson correlations were computed between all independent variables to eliminate variables that were strongly correlated ($R > 0.60$). Based on this procedure, the variables loam and silt were eliminated because they were strongly correlated with sand, which was the only soil texture variable used in the model.

Processes Driving Land-cover Changes

To determine the relative importance and spatial pattern of major processes causing land-cover changes, a conceptual graph linking the processes we hypothesized to be important with the different land-cover categories was developed (Figure 3). Each process can be described by parallel changes in two land-cover categories going in opposite directions; for example, farm abandonment includes a decline in agricultural land paralleled by an increase in forest cover. We selected sections that fulfilled such combined criteria of land-cover changes by

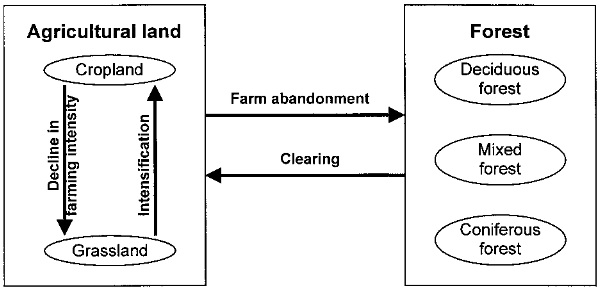

Figure 3. Conceptual graph depicting four major processes of land-cover change.

comparing the maps of land cover in 1938 and in 1992. A threshold of 15% of the area of a given section showing changes in both directions was used, based on the fact that changes in land cover for the whole study region were less than 15% in all categories (Figure 4c). This means that, for example, if the area of a section covered by agricultural land was reduced by at least 15%, and at the same time forest cover in the same section increased by at least 15% of the area, this section would fulfill the criteria of abandonment.

The following processes were considered: decline of agricultural land and increase of forest (farm abandonment), decline of forest and increase of agricultural land (clearing), decline of grassland and increase of cropland (intensification of farming), and decline of cropland and increase of grassland (decline in farming intensity) (Figure 3). Maps of the location of the sections showing the different land-cover transitions were drawn to detect spatial pattern, and abiotic and socioeconomic characteristics of the sections selected were summarized. Ground truthing was used to verify how plausible it was that the hypothesized processes were responsible for the changes in land cover.

Results

Land Cover, 1938 and 1992

Patterns of land cover. In 1938, about 54% of the study area was covered by agricultural land, with 44% in cropland and 10% in grassland (Figure 4a). Forests covered 32% of the area, being mostly deciduous forest (27%) with little coniferous forest (5%). The 10% covered by wetlands were mostly open (5%) and forested wetlands (4%). In 1992, agricultural land was reduced to 46%, with cropland on 32% of the study area and grassland on 14% (Figure 4b). Thus, the decline in cropland was partially compensated by an increase in grassland (Figure 4c). In contrast, forests increased during the study period, covering 38% in 1992. Changes in forest were due to an increase in deciduous forests—covering 30% of the study area in 1992—and mixed forests, which were nearly absent in 1938 but now account for 4% of the land cover. Coniferous forests declined slightly to 4% of the area. The small increase in wetlands (11% in 1992) was due to an increase in shrubby (from 1% to 2%) and forested wetlands (from 4% to 5%). However, open wetlands declined to 4%.

Examination of the spatial distribution of land cover in 1938 and 1992 revealed distinctive regional patterns (Figure 5a). In 1938, agricultural land was much more prevalent in areas outside the Central Sand Plains (CSP) (Figure 1). There was no grassland in the CSP. The spatial distribution of grassland changed completely from 1938 to 1992, with most grassland now occurring in the CSP region. The general decline in cropland was most pronounced in the area near Portage and along the lower part of the Wisconsin River. Not surprisingly, forest distribution shows the reverse pattern (Figure 5b): Forest cover in 1938 was concentrated in the CSP region but also along the lower part of the Wisconsin River. This pattern became even more distinct in 1992. In both years, coniferous forests were concentrated in the CSP region.

Abiotic and socioeconomic variables. Among land-cover categories in 1938, multiple linear regressions using three abiotic and two socioeconomic variables captured 6%–36% of the variation among sections (= Combined Model in Table 3). Using the same variables, 9%–46% of the variation was captured for land cover in 1992. Using abiotic variables alone, 6%–35% of the variation was explained in 1938 and 6%–46% was explained in 1992 (= Abiotic in Table 3). The socioeconomic variables alone explained 1%–6% of the variation in 1938 and 1%–9% in 1992 (= Soc. Econ. in Table 3). Including the additional socioeconomic variables available for 1992 (that is, population change 1938–90 and proportion of land managed by the DNR) increased the amount of variation explained to 6%–26%. The combined model including all variables explained 13%–48% of the variation in different land-cover categories.

Explaining land-cover categories. There was some consistency in the land-cover classes for which variation was best explained in 1938 and 1992. For both years, primary and secondary categories of forest always obtained higher R^2 values than the agricultural-land categories. Higher R^2 values were obtained for coniferous forests than for deciduous forests; and in both years, the R^2 values for coniferous forests were the highest of all land-cover

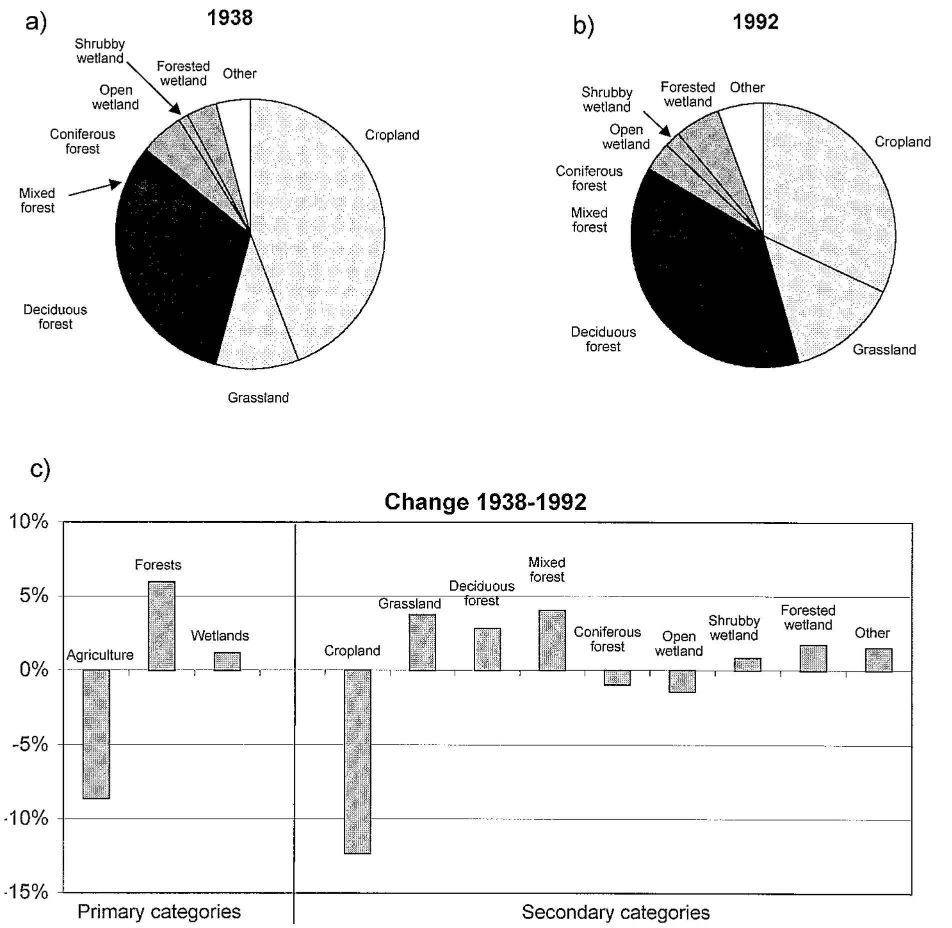

Figure 4. Land cover (a, b) and land-cover changes (c) in the study region for 1938 and 1992. The different shades of gray in (a) and (b) correspond with the three primary categories, which in a hierarchical classification are differentiated into secondary categories.

categories (R^2 for 1938 = 0.36, R^2 for 1992 = 0.46). Among the secondary categories of agricultural land, in 1938 variation in grassland cover was explained better (R^2 = 0.31) than cropland (R^2 = 0.06). In 1992, however, grassland reached lower values (R^2 = 0.09) but cropland was better modeled (R^2 = 0.19). Grassland was the only secondary land-cover category that showed a decrease in amount of variation explained, since the models for 1992 did explain more of the variation in deciduous forest, coniferous forest, and cropland than they did for 1938.

Land-cover Change

Major types of land-cover change and their spatial distribution. The most important land-cover change was a decline in agricultural land and an increase in forest. A total of 727 of the 3403 sections, or 21% of our study area, fulfilled the criteria for this conversion. The reverse transition (a decline in forest paralleled by an increase in agricultural land) was observed in 103 sections, or 3% of the study area. The second most important land-cover change was a decline in cropland paralleled by an increase in grassland, detectable in 546 sections, or 16% of the study area. The reverse transition, (a decline in grassland and an increase in cropland) was visible in 91 sections, or 3% of the study area.

Mapping the sections reveals distinctive spatial patterns (Figure 6). The decline in agricultural land and increase in forest occurred throughout the study area, but it was most prevalent in the mid to lower parts of the Wisconsin River valley. The opposite transition (a decline in forest and increase in agricultural land) is almost entirely restricted to the CSP region (Figure 1). Sections showing a decline in cropland and an increase in grassland are mostly located in the mid to upper part of the Wisconsin River valley, outside the WCR region. The decline in grassland paralleled by an increase in cropland was largely limited to an area south of the Wisconsin River, toward the confluence with the Mississippi River.

In our analysis of land-cover changes, we used a system of nested categories (Figure 3). Whereas some types of land-cover changes were defined as changes between primary categories (for example, transitions between forest and agricultural land),

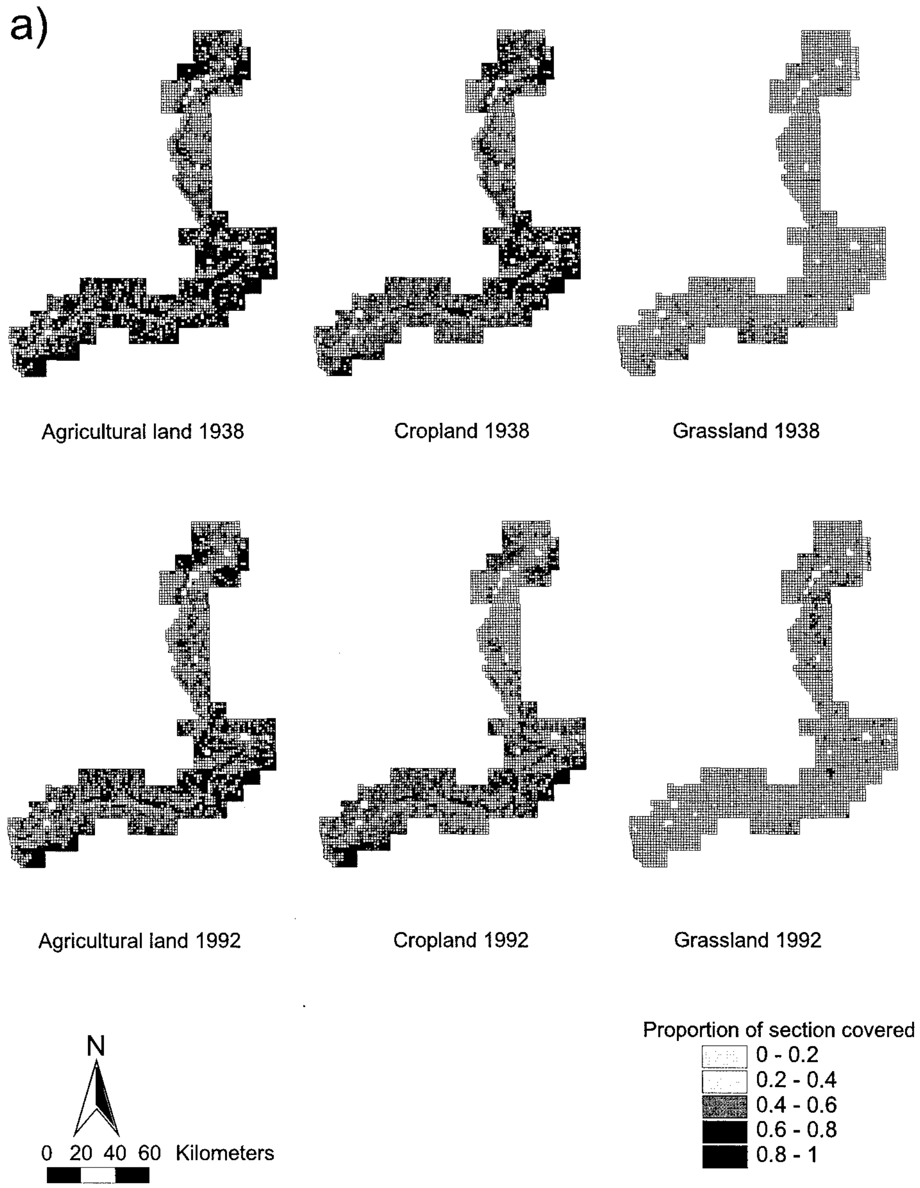

Figure 5a. Maps of land-cover classes for 1938 and 1992 depicting the categories of agricultural land. (Figure continues on next page.)

others were defined as changes between secondary categories (for example, transitions between grassland and cropland). This allowed us to determine the impact of primary-level land-cover changes on the secondary-level categories. Therefore, we determined the mean proportions of land-cover categories for the sections for each of the four transitions under study (Figure 7). To indicate which categories were used in defining a transformation type, we highlighted the respective bars in Figure 7. The decline in agricultural land and increase in forest is explained primarily as a conversion of cropland to deciduous forests. This means that in the northern part of the study region the decline in cropland was paralleled by an increase in grassland; whereas in the southern part of the study region, the decline in cropland was paralleled by an increase in deciduous forest. Evaluating land-cover changes within the sections falling into the four types of land-cover changes (Figure 7) also enables us to specify the transitions between agricultural land and forest as depicted in Figure 3. The decline in agricultural land and increase in forest included mostly a decline in cropland paralleled by an increase in deciduous forests. The shift in the opposite direction (a decline in forest and an increase in agricultural land) is characterized by a decrease in deciduous as well as coniferous forests paralleled by an increase in grassland.

The results for the transformation of forests to agricultural land are counterintuitive. As shown in

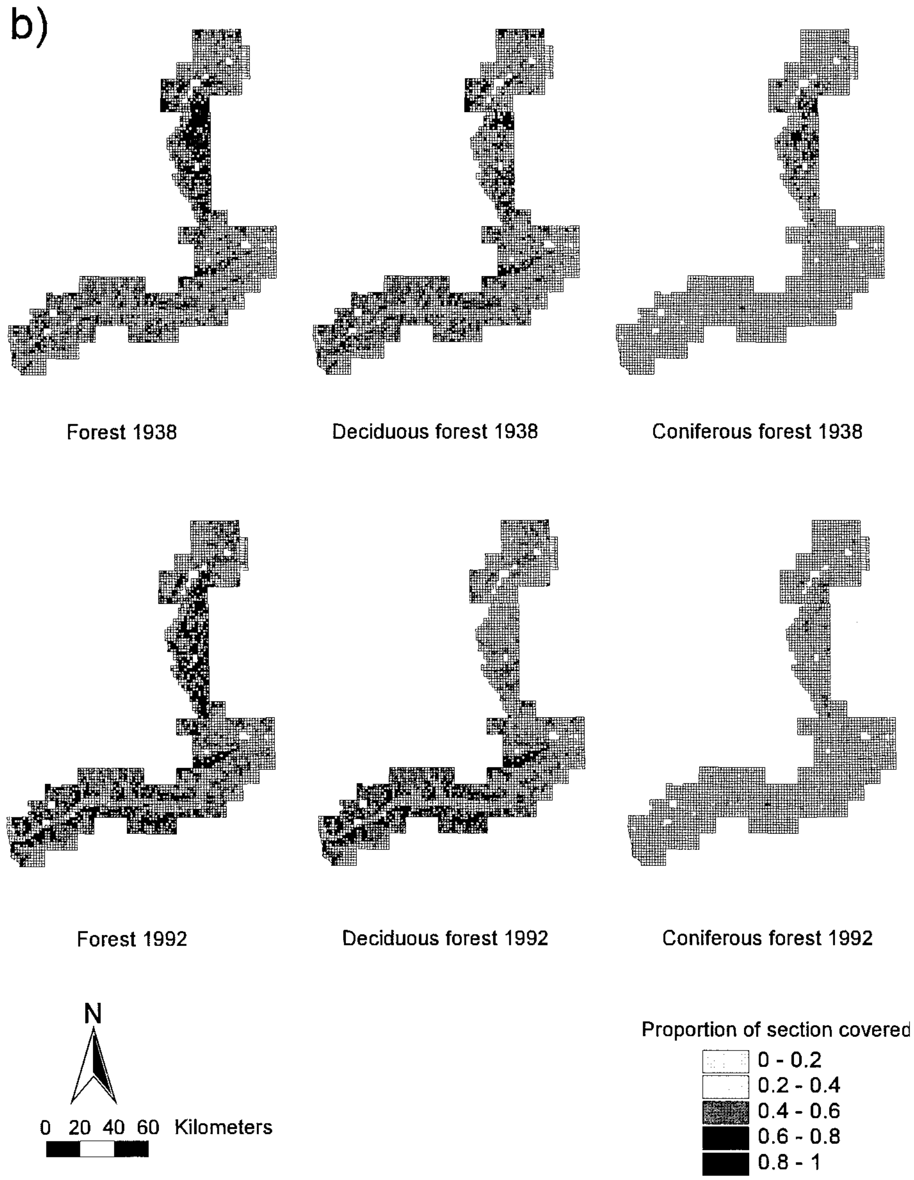

Fig. 5b. Maps of land cover classes for 1938 and 1992 depicting the categories of forest.

Figure 7, this conversion is caused by a reduction in coniferous and deciduous forests and an increase in grassland. Given the general decline in agriculture in our study area, such a conversion makes no economic sense. Based on ground proofing, we assume that a large portion of the land classified as grassland for 1992 was part of the rotation cycle of conifer plantations, probably mostly jack pine (*Pinus banksiana*) and red pine (*Pinus resinosa*). Thus, the decline in forest paralleled by an increase in agricultural land may not represent the clearing of land for farm establishment, but merely a temporary increase in grassland due to conifer rotation. Therefore, this type of land-cover change should correctly be termed "from forest to temporary grassland." Commercial rotation ages for jack pine, which is mostly used as pulpwood, are generally between 40 to 70 years (Benzie 1977). An extensive planting program for jack pine was initiated in the North Central States in the 1930s (Benzie 1977), and many of those stands might have been cut in the decade prior to the satellite images used to produce WISCLAND. Since crown closure in the plantation does not occur until about 10 years after the clear cut (V. Radeloff personal communication), it is possible that only about two-thirds of the actual coniferous plantations in the study area were classified as coniferous plantations for 1992. The coniferous plantations in the study area are located near pulp and paper mills along the Wisconsin River in Stevens Point, Plover, Wisconsin Rapids, Port Edwards, and Nekoosa (McGovern 1979; Wisconsin Cartographers' Guild 1998).

Table 3. Results of Multiple Regression Analyses on Abiotic and Socioeconomic Variables with Land Cover in 1938 and 1992

	R^2 Combined model, abiotic + Soc. Econ.	R^2 Abiotic Variables Only	Sand	Depth to Bedrock	Available Water Capacity	R^2 Soc. Econ. Variables Only	Population Density 1940/90	Farm Economy 1937/1992
1938								
Agricultural land	0.1360	0.1271	−−−	+	−	0.0205		+
Forest	0.2347	0.2125	+++	−−−		0.0283	−	−
Cropland	0.0625	0.0566	−	+	−	0.0100	+	+
Grassland	0.3090	0.2909	−−−−		−	0.0173		+
Deciduous forest	0.1247	0.1015	+	−−		0.0052	−	−
Coniferous forest	0.3604	0.3503	+++++		−	0.0583		−−
1992								
Agricultural land	0.0896	0.0715	−	+	−	0.0381	−	+
Forest	0.2628	0.1815	+	−	−−−	0.0331	−	−
Cropland	0.1890	0.1482	−−−	+		0.0883	−	+
Grassland	0.0901	0.0648	++	+	−	0.0539		−−
Deciduous forest	0.3265	0.2464	−	−−−−	−	0.0141	−	−
Coniferous forest	0.4613	0.4583	++++++	+	−	0.0728	+	−

R^2 Value		
0–0.05	+	−
0.05–0.1	++	−−
0.1–0.2	+++	−−−
0.2–0.3	++++	−−−−
0.3–0.4	+++++	−−−−−
>0.4	++++++	−−−−−−

The size and type of symbols represent the relative significance of a variable based on the R^2 values.
Models were chosen through stepwise selection with variables remaining in the model if significant at $P = 0.05$.

Characteristics of areas prone to the different types of land-cover change. It is of interest to know what abiotic and socioeconomic conditions characterize the areas prone to a certain type of land-cover change. We therefore compared the average values of the variables used in the regression model in the sections where the major types of land-cover changes occurred. The proportions of sand, loam, and silt revealed major differences. No soil texture class was dominant in sections that experienced a decline of agricultural land and an increase of forest (Figure 8a), but silt was most common (42%). Sections where forests were converted to temporary grassland were dominated by sandy soils (82%). In areas where cropland was reduced and grassland increased, we also find mostly sandy soils (48%). A very distinct pattern is visible for soil texture characteristics in sections of declining grasslands and increasing croplands; 77% of soils were classified as silty soils, and the sections were characterized by the highest available water capacity among the four types of land-cover conversion (Figure 8b).

There were distinct differences in socioeconomic factors in areas of differing land-cover transitions. Sections changing from cropland to grassland were the most densely populated areas in both 1938 and 1992 (Figure 8c). In areas of declining grassland and increasing cropland, population density decreased slightly.

The similarity of the two proxy variables for farm economic status is quite striking; the ranking of the four land-cover transition types with regard to this variable remained the same from 1938 to 1992 (Figure 8d). Given the very different information used to calculate the two variables (number of trac-

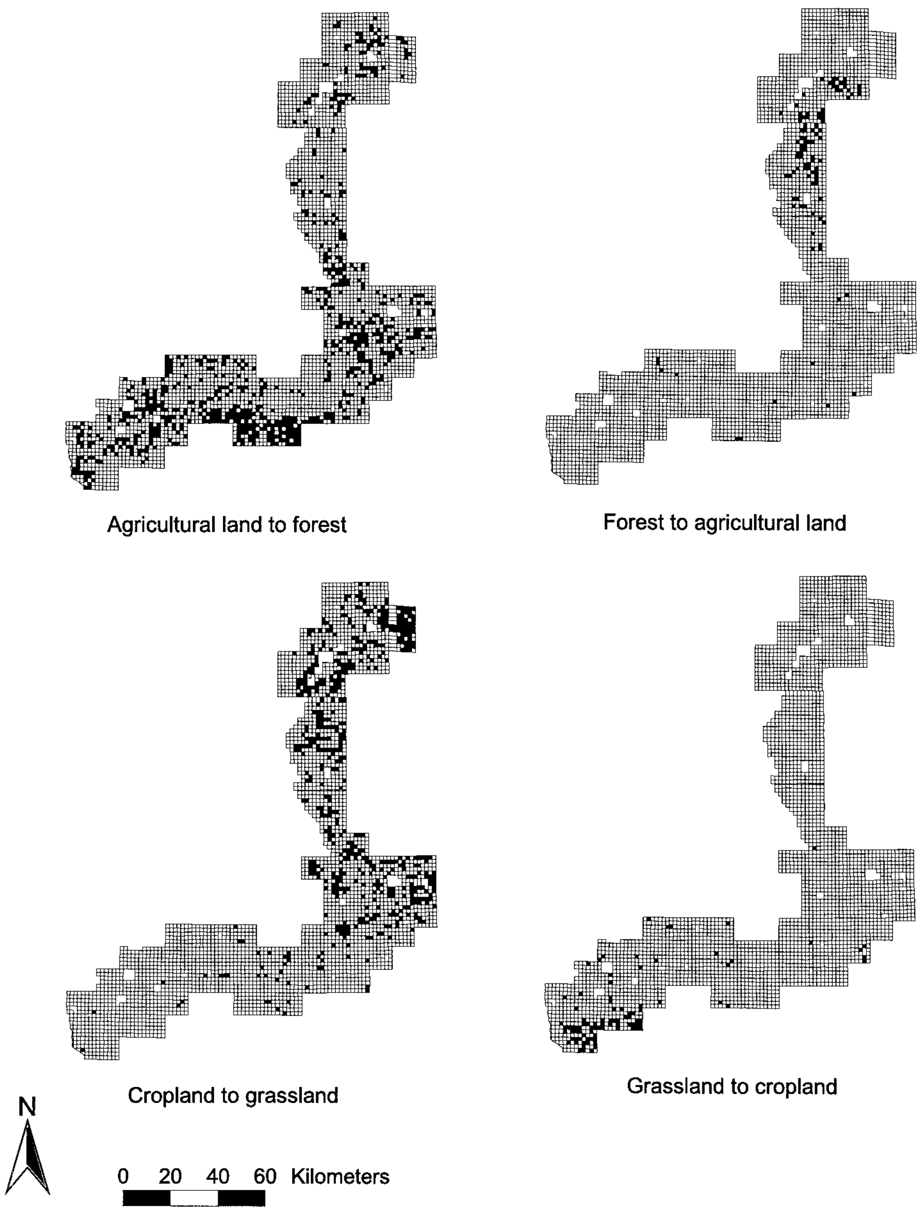

Figure 6. Maps of sections meeting the criteria for each of the four land-cover transitions under study.

tors in 1937; ratio of high-income vs low-income farms in 1992) suggests that the proxies indeed reflect some common feature of farm economic status. The outstanding feature in Figure 8d is the bar showing a decline in grassland and an increase in cropland. In 1937, the sections representing this land-cover transition had the highest number of tractors per farm among the four types of transitions; more than one in three farms had a tractor. In 1992, it was an area dominated by high-income farms.

Processes Driving Land-cover Changes

Our results show that the sections within the four major types of land-cover changes have distinct spatial patterns and differ in abiotic and socioeconomic features. It remains to be seen if the changes detected in land cover from those four groups of sections are driven by the four main processes proposed in Figure 3 (farm abandonment, clearing of forests for farmland, intensification of farming, and decline in farming intensity).

From agricultural land to forest. The change from agricultural land to forest predominantly represented a decline of cropland paralleled by an increase in deciduous forest (Figure 7) taking place on comparatively shallow soils (Figure 8b). This is consistent with farm abandonment.

From forest to agricultural land/temporary grassland. As revealed by ground proofing, the apparent conversion from forest to agricultural land was in many

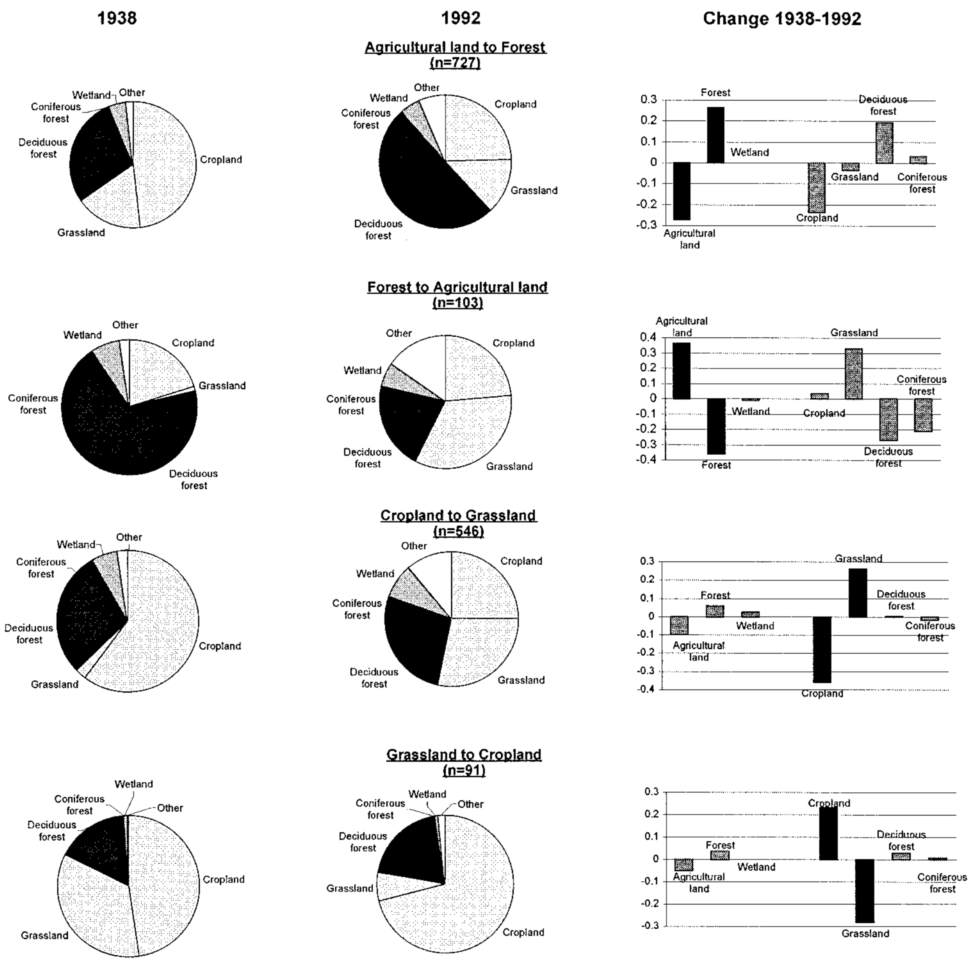

Figure 7. Land cover and land-cover changes in the sections meeting the criteria for the four land-cover transitions for 1938 and 1992. Categories used to define transition types are depicted in black in the bar graphs.

places a conversion from forest to temporary grassland (Figure 7). This conversion took place mostly on the very sandy soils of the CSP region (Figure 8b). Generally, the changes do not reflect a conversion of forests to agricultural land.

From cropland to grassland. The decline in cropland paralleled by an increase in grassland occurred primarily on more sandy and deeper soils (Figure 8a) than soils from sections showing farm abandonment (that is, the conversion of agricultural land to forest), but with similar available water capacities (Figure 8b). Cropland–grassland transition areas were—and still are—located in the most populated parts of the study area (Figure 8c), and farm economic status, as indicated by proxy variables, is considered low (Figure 8d). Thus, these areas are not prime farmland, despite being predominantly cropland in 1938 (Figure 7). In 1934, approximately 50% of all farm operators in the counties north of Portage worked outside their farms for income, compared to 20%–25% in the counties south of Portage (Wisconsin Crop Reporting Service 1938). This suggests that the high percentage of cropland in the northernmost part of the study area in 1938 (Figure 5a) was not indicative of a thriving agricultural economy. Cropland from 1938 that became grassland by 1992 might also be in an intermediate stage in the process of farm abandonment; that is, it might turn into forest during the next decades. We therefore assume that a decline in farming intensity is very probable in those areas.

From grassland to cropland. The sections where a decline in grassland was paralleled by an increase in cropland are concentrated in a small area in the southernmost part of the study area. The soils are very silty and have a high average water holding capacity (Figure 8a, b). The decline in population (Figure 8c) suggests that no other major employers moved into the area, and economic centers, such as Madison, were outside the commuting distance. However, these sections had the highest values for both farm economic proxies, which indicates that the process of intensification seems to be correctly assigned to those sections.

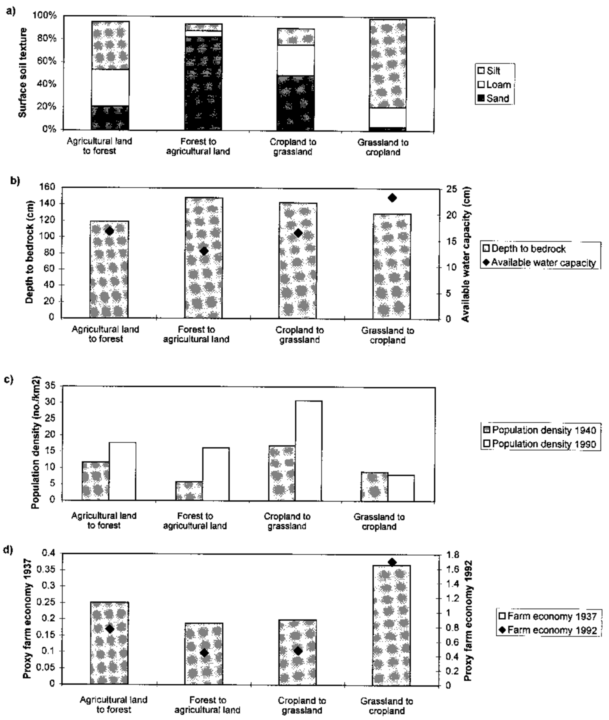

Figure 8. Summary of the abiotic and socioeconomic characteristics of the sections meeting the criteria for the four land-cover transitions for 1938 and 1992: (**a**) surface soil texture, (**b**) depth to bedrock and available water capacity, (**c**) population density, and (**d**) proxy for farm economic status.

Discussion

Land Cover and Land-cover Change

We hypothesized that agriculture would become more restricted to favorable soils, which would increase the amount of variation in land-cover explained by abiotic variables in 1992 vs 1938. Comparing the R^2 values for abiotic factors in models of cropland in 1938 with the results for models for 1992 reveals some evidence of such an effect (Table 3); the R^2 value for abiotic variables increased from 0.06 in 1938 to 0.15 in 1992. This was primarily due to an increase in the explanatory power of the variable sand; in 1992, cropland was less likely to be found on sandy soils than it was in 1938 (Table 3), a finding that supports our hypotheses. Variation in grassland cover, the other secondary category of agricultural land, was much harder to explain in 1992 ($R^2 = 0.09$) than in 1938 ($R^2 = 0.31$). This might be partly due to the fact that grassland includes the temporary grassland after a clear cut. Consequently, model performance for the primary category of agricultural land declined. Even as abiotic variables became more important in explaining variation in cropland from 1938 to 1992, their relative importance in the combined models declined due to an increase in explanatory power of socioeconomic variables. However, such a comparison between different groups of variables depends primarily on the variables included in the model. This is illustrated by the increase in explanatory power of the socioeconomic variables, if the additional variables of population change and proportion of the land managed by the DNR are included. Still, including socioeconomic variables improved model performance in every case, even if the improvement was sometimes marginal.

Forest cover was generally better explained by the models, especially coniferous forest. The high explanatory power of sand in the regression models (Table 3) is due to the concentration of coniferous forests on the sandy soils of the CSP (Figures 1 and 5). As shown in the presettlement records, the CSP were predominantly covered by pine forests (for example, see Curtis 1959).

Considerable variation in land-cover change remains unexplained by these models, but this is not surprising given the complexity and multiple causes of dynamics in human-influenced landscapes. Other studies have explained a similarly low percentage of variability in land use and land-cover change (for example, see Schnaiberg 2000; Schnaiberg and others in press) or have emphasized the significance of explanatory variables rather than variation explained (for example, see Turner and others 1996; Wear and Bolstad 1998). Relatively simple statistical models that rely on quantitative responses and drivers may not be well suited to capturing other important factors, such cultural attitudes, lifestyles, standards of living, and politics, that also influence land-use decisions (for example, see Heasley and Guries 1998; Cronon 2000). Data that are consistent through time may not be available for other important variables, such as land prices and rents. Structural changes in landscapes, such as highway construction and development or shifts in markets and urban centers, may introduce new drivers to the system or change the influence of others. Land-use patterns also result from influences at many scales; for example, land-use decisions are influenced by local, state, and federal regulations and laws (Dale and others 2000). These variables are partly responsible for the unexplained variation in our models. Although some of these factors will be impossible to quantify, others could be included as dummy variables—for example, the validity area of certain laws affecting land use and land cover. Explaining and predicting land-use patterns remains an important but very complex interdisciplinary challenge (Bürgi and Russell 2001).

Processes Driving Land-cover Changes

The results suggest that farm abandonment, a decline in farming intensity, and an intensification of farming contributed to land-cover changes. In a study area in the southern part of Wisconsin, Auclair (1976) found a general intensification of agriculture accompanied by a reduction in cropland and an increase in forest cover for the period 1934–61. We confirmed the increase in forest cover and a concentration of agricultural activities on areas with favorable site conditions for the landscape along the Wisconsin River and the period 1938–92.

Our method of hypothesizing and testing major anthropogenic processes proved to be a useful tool to detect very different, even opposite, processes shaping land-cover changes in different parts of the study region. Such methods of studying human-induced driving forces of landscape changes are needed to make landscape ecological principles more applicable to landscapes dominated by human impacts.

CONCLUSIONS

In 1992, nearly half of the study area was still classified as agricultural land. Thus, landscape changes in the study area will continue to be driven mainly by farm-level decisions. Because farming in Wisconsin is still largely carried out on family farms (Olmstead 1997), the set of factors relevant for the future of this agricultural landscape is different than that in a region dominated by large-scale industrial agriculture. Whether a family farm can continue to operate depends on a variety of impacts from, for example, the economy (such as the availability of off-farm employment, the potential to expand the operation, the possibility of alternative land uses such as new housing developments, the availability of borrowed funds from commercial sources [Dorner 1981]), culture (such as the motivation of the family to keep the farm running despite modest income, or the demand for organic products), and technology (such as new varieties of seeds, new farming machines) (Olmstead 1997).

Today, studies of land-cover change are usually based on remote sensing data. In our study, we faced the intriguing situation that some of the land classified as grassland is in fact part of a clear-cutting cycle; that is, these areas are agricultural with respect to land-cover and ecological characteristics but part of forestry in terms of land use. Therefore, careful consideration of the differences between land cover and land use is crucial to avoid misinterpretation of remote sensing data.

The study of landscape history deserves more attention, because the past might help to explain current ecological structure and function (for example, see Foster 1992; Motzkin and others 1996, 1999; Fuller and others 1998; Foster and others 1998; Harding and others 1998). In addition, it may be important for designing ecologically informed land-management practices (for example, see Cronon 2000; Radeloff and others 2000). Landscapes are cultural as well as natural constructs, and this study has identified areas for which the current status of the vegetation or soils in the Wisconsin River floodplain and watershed may be influenced by legacies of past land use. Our results also describe an increase in the natural vegetation classes in areas that were more marginal for farming, and this trend is consistent with that reported for other locations (see for example, Turner and others 1996) and for sections of the 100-year floodplain of the Wisconsin River (Freeman and others unpublished). Floodplain forest is important for many species and processes (Naiman and Décamps 1997), and connectivity of these areas is critical to maintaining ecosystem services (see, for example Knutson and Klaas 1998).

Our method of hypothesizing and testing major anthropogenic processes affecting land cover provides information about the characteristics of areas that show certain types of changes. When combined with regression approaches, this type of regional characterization may enhance our understanding of land-cover change in other regions.

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REFERENCES

Auclair AN. 1976. Ecological factors in the development of intensive-management ecosystems in the midwestern United States. Ecology 57:431–4

Barnes WJ. 1997. Vegetation dynamics on the floodplain of the lower Chippewa River in Wisconsin. J Torrey Bot Soc 124: 189–97

Benzie JW. 1977. Manager's handbook for jack pine in the North Central States. General technical report no. NC-32 USDA Forest Service, 22 p.

Bürgi M, Russell EWB. 2001. Integrative methods to study landscape changes. Land Use Policy 18:9–16

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8:559–68

Census of Agriculture. 1992. USDA National Agricultural Statistics Service. Prepared by the Bureau of the Census. http://govinfo.kerr.orst.edu/cgi-bin/ag-zip

Conzen MP. 1997. The European settling and transformation of the Upper Mississippi Valley lead mining region. In: Ostergren RC, Vale TR, editors. Wisconsin land and life. Madison (WI): University of Wisconsin Press. p 163–96

Cottam G, Loucks OL. 1965. Early vegetation of Wisconsin. University of Wisconsin–Extension. Geological and Natural History Survey, Madison, WI

Cronon W. 2000. Resisting monoliths and tabulae rasae. Ecol Appl 10:673–5

Curtis JT. 1959. The vegetation of Wisconsin. Madison (WI): University of Wisconsin Press

Dale VH, Brown S, Haeuber R, Hobbs NT, Huntly N, Naiman RJ, Riebsame WE, Turner MG, Valone T. 2000. Ecological principles and guidelines for managing the use of land. Ecol Appl 10:639–70

Dorner P. 1981. Economic and social changes on Wisconsin family farms. Madison (WI): Research Division of the College of Agricultural and Life Sciences, University of Wisconsin–Madison, R3105

Dorney JR. 1981. The impact of Native Americans on presettlement vegetation in southeastern Wisconsin. Wis Acad Sci Arts Lett 69:26–36

Foster DR. 1992. Land-use history (1730–1990) and vegetation dynamics in central New England, USA. J Ecol 80:753–72

Foster DR, Motzkin G, Slater B. 1998. Land-use history as long-term broad-scale disturbance: regional forest dynamics in central New England. Ecosystems 1:96–119

Freeman RE, Stanley EH, Turner MG. Analysis and conservation implications of landscape change in the floodplain of the Wisconsin River, USA. (unpublished)

Fuller JL, Foster DR, McLachlan JS, Drake N. 1998. Impact of human activity on regional forest composition and dynamics in central New England. Ecosystems 1:76–95

Harding JS, Benfield EF, Bolstad PV, Helfman GS, Jones EBD III. 1998. Stream biodiversity: the ghost of land use past. Proc Natl Acad Sci 95:14843–7

Heasley L, Guries RP. 1998. Forest tenure and cultural landscapes: environmental histories in the Kickapoo Valley. In: Jacobs HM, editor. Who owns America? Social conflict over property rights. Madison (WI): University of Wisconsin Press, pp 182–207

Iverson LR. 1988. Land-use changes in Illinois, USA: the influence of landscape attributes on current and historic land use. Landscape Ecol 2:45–61

Johnson HB. 1976. Order upon the land: the U.S. rectangular land survey and the Upper Mississippi country. New York: Oxford University Press

Jordan TE, Correll DL, Weller DE. 1997. Relating nutrient discharges from watersheds to land use and streamflow variability. Water Resources Res 33:2579–90

Jordan TE, Correll DL, Weller DE. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. J Environ Quality 22:467–73

Kline VM, Cottam G. 1979. Vegetation response to climate and fire in the Driftless Area of Wisconsin. Ecology 60:861–8

Knutson MG, Klass EE. 1998. Floodplain forest loss and changes in forest community composition and structure in the Upper Mississippi River: a wildlife habitat at risk. Nat Areas J 18: 138–50

Lange KI. 1990. A postglacial vegetational history of Sauk County and Caledonia Township, Columbia County, South Central Wisconsin. Technical bulletin no. 168. Madison (WI): Department of Natural Resources.

Lee RG, Flamm RO, Turner MG, Bledsoe C, Chandler P, DeFerrari C, Gottfried R, Naiman RJ, Schumaker N, Wear D. 1992. Integrating sustainable development and environmental vitality. In: Naiman RJ, editor. New perspectives in watershed management. New York: Springer-Verlag. p 499–521

Leopold A. 1949. A sand county almanac. New York: Oxford University Press

Lillesand T, Chipman J, Nagel D, Reese H, Bobo M, Goldmann R. 1998. Upper Midwest GAP analysis image processing protocol. Document no. 98–G001. US Geological Survey, Environmental Management Technical Center.

McGovern JN. 1979. Development of the paper manufacturing industry in Wisconsin. In: Hernandez RR, editor. Some events in Wisconsin's forest history. Wausau (WI): Forest History Association of Wisconsin

Martin L. 1965. The physical geography of Wisconsin. 3rd ed. Madison (WI): University of Wisconsin Press, p 26–52

Mladenoff DJ, Howell EA. 1980. Vegetation change on the Gogebic Iron Range (Iron County, Wisconsin) from the 1860s to the present. Wisc Acad Sci Arts Lett 68:74–89

Mladenoff DJ, White MA, Pastor J, Crow TR. 1993. Comparing spatial pattern in unaltered old-growth and disturbed forest landscapes. Ecol Appl 3:294–306

Motzkin G, Foster DR, Allen S, Harrod J, Boone R. 1996. Controlling site to evaluate history: vegetation patterns of a New England sand plain. Ecol Monogr 66:345–65

Motzkin G, Wilson P, Foster DR, Allen A. 1999. Vegetation patterns in heterogeneous landscapes: the importance of history and environment. J Veg Sci 10:903–20

Naiman RJ. 1996. Water, society and landscape ecology. Landscape Ecol 11:193–6

Naiman RJ, Magnuson JJ, McKnight DM, Stanford JA, editors. 1995. The freshwater imperative: a research agenda. Washington (DC): Island Press

[NHFEU] National Hierarchical Framework of Ecological Units, [WDNR] Wisconsin Department of Natural Resources. 1999. Ecological units of the eastern United States—first approximation. http://www.dnr.state.wi.us/org/at/et/geo/metadata/ecobnd/feunw92d.html

Olmstead CW. 1997. Changing technology, values, and rural landscapes. In: Ostergren RC, Vale TR, editors. Wisconsin land and life. Madison (WI): University of Wisconsin Press. p 355–75

Ostergren RC. 1997. The Euro-American settlement of Wisconsin, 1830–1920. In: Ostergren RC, Vale TR, editors. Wisconsin land and life. Madison (WI): University of Wisconsin Press. p 137–62

Pan D, Domon G, de Blois S, Bouchard A. 1990. Temporal (1958–1993) and spatial patterns of land use changes in Haut-Saint-Laurent (Quebec, Canada) and their relation to landscape physical attributes. Landscape Ecol 14:35–52

Paquette S, Domon G. 1997. The transformation of the agroforestry landscape in the nineteenth century: a case study in southern Quebec (Canada). Landscape Urb Planning 37:197–209

Radeloff VC, Mladenoff DJ, Boyce MS. 2000 A historical perspective and future outlook on landscape scale restoration in the northwest Wisconsin pine barrens. Restoration Ecol 8:119–26

Riebsame WE, Parton WJ, Galvin KA, Burke IC, Bohren L, Young R, Knop E. 1994. Integrated modeling of land use and cover change. BioScience 44:350–6

Riera J, Voss PR, Carpenter SR, Kratz TK, Lillesand TM, Schnaiberg JA, Turner MG, Wegener MW. 2001. Nature, society and history in two contrasting landscapes in Wisconsin, USA: interactions between lakes and humans during the twentieth century. Land Use Policy 18:41–51

SAS Institute. 1990. SAS/STAT User's Guide, Version 6. 4th ed.; vols 1 and 2. Cary (NC): SAS Institute

Schnaiberg JA 2000. Breaking waves: an analysis of lakeshore development in Vilas County, Wisconsin, USA. MS thesis (Land Resources), University of Wisconsin, Madison.

Schnaiberg J, Riera J, Turner MG, Voss PR. Explaining human settlement patterns in a recreational lake district: Vilas County, Wisconsin, USA. Environ Manage. (in press).

Silbernagel J, Martin SR, Gale MR, Chen J. 1997. Prehistoric, historic, and present settlement patterns related to ecological hierarchy in the Eastern Upper Peninsula of Michigan, U.S.A. Landscape Ecol 12:223–40

Soil Conservation Service. 1995. State soil geographic (STATSGO) data base. Miscellenous publication no. 1492. Washington (DC): USDA Department of Agriculture, Soil Conservation Service.

Spies TA, Ripple WJ, Bradshaw GA. 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. Ecol Appl 4:555–68

State of Wisconsin. 1936. Bulletin no. 3. Division of Land Economic Inventory, Executive Office.

Tans W. 1976. The presettlement vegetation of Columbia County, Wisconsin in the 1830's. Technical bulletin no. 90. Madison (WI): Department of Natural Resources.

Turner MG, Wear DN, Flamm RO. 1996. Land ownership and land-cover change in the Southern Appalachian Highlands and the Olympic Penninsula. Ecol Appl 6:1150–72

US Census Bureau. 1940. Washington (DC): US Census Bureau

US Census Bureau. 1990. Washington (DC): US Census Bureau

Wear DN, Bolstad P. 1998. Land-use changes in southern Appalachian landscapes: spatial analysis and forecast evaluation. Ecosystems 1:575–94

Wear DN, Turner MG, Naiman RJ. 1998. Land cover along an urban–rural gradient: implications for water quality. Ecol Appl 8:619–30

White MA, Mladenoff DJ. 1994. Old-growth forest landscape transitions from pre-European settlement to present. Landscape Ecol 9:191–206

Wisconsin Cartographers' Guild. 1998. Wisconsin's past and present: a historical atlas. Madison (WI): University of Wisconsin Press

Wisconsin Crop Reporting Service. 1938. Wisconsin agriculture. Statistical bulletin no. 188

Yin Y, Nelson JC, Lubinski KS. 1997. Bottomland hardwood forest along the Upper Mississippi. Nat Areas J 17:164–73

Zar JH. 1984. Biostatistical analysis. Englewood Cliffs (NJ): Prentice-Hall.