ANALYSIS AND CONSERVATION IMPLICATIONS OF LANDSCAPE CHANGE IN THE WISCONSIN RIVER FLOODPLAIN, USA

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Abstract. River floodplain landscapes are diverse and dynamic, yet little is known about long-term changes in land-cover patterns in these systems. We quantified floodplain land-cover change between the 1930s and the 1990s along nine 12–21-km reaches of the Wisconsin River by analyzing and digitally classifying 200 historic aerial photos corrected against modern orthophotographs. Several metrics of landscape structure were used to determine changes in amount and connectivity of deciduous forest, wetlands, grassland, and agriculture within the 100-yr floodplain. Deciduous forest increased by up to 51% between the 1930s and the 1990s. However, number of patches declined, and edge density increased in almost every reach, indicating that amount and connectivity of forest cover increased but that forest patches became more complex in shape. Grasslands declined, and the number, edge density, and mean size of grassland patches illustrated a progression to fewer, smaller, isolated remnants. Wetland patch dynamics demonstrated complex and divergent patterns, as wetland cover decreased in northern reaches, increased in patch density but not mean patch size in the central region, and increased in both patch density and patch size in the south. Agricultural areas declined in eight of nine reaches, and tended to fragment into fewer, smaller patches. These trends underscore a complicated and dynamic pattern of landscape change over a relatively short time scale.

   We explored realistic conservation scenarios to determine how disparate strategies would affect floodplain forest connectivity in four of the study reaches. One approach filled gaps in the buffer zone immediately adjacent to the river channel; the other reverted small or large agricultural patches to forest cover. Filling buffer zone gaps resulted in dramatic changes in forest connectivity in one half of the reaches, whereas greatest forest connectivity was gained by reverting agricultural patches to forest in the other half of the reaches. These scenarios emphasize that the way that forest conservation occurs (e.g., filling gaps vs. patch conversion) is just as significant as how much land is actually protected, and the ideal management option must be tailored to the specific land-cover arrangements of a given river reach. In addition to evaluating changes in forest connectivity, the number of landowners that would be affected by conservation strategies was determined. Greatest increases in forest connectivity under the buffer scenarios involved from 15 to 21 different landowners, whereas the greatest increases under the reversion scenarios affected from 14 (using several large agricultural parcels) to 67 (using many small parcels) landowners. Thus the number of landowners affected by different management scenarios represents a critical constraint on idealized conservation plans. Such scenarios may prove useful in floodplain management and facilitate synthesis of ecological research and land management.

   Key words: conservation; floodplain forests; forest connectivity; land-cover change; management scenarios; orthophotography; riparian buffer; Wisconsin River, USA.

INTRODUCTION

   River floodplain landscapes are among the most diverse and dynamic habitats on Earth (Naiman et al. 1993), and floodplains provide a wide range of ecosystem goods and services including flood control, water quality improvement, recreation, enhanced property values, and aesthetic appeal (Costanza et al. 1997, Postel and Carpenter 1997, Haeuber and Michener 1998). Floodplain forests also support a large proportion of regional biodiversity and productivity (Malanson 1993, Naiman et al. 1993) and are hotspots of biogeochemical activity. Thus these environments have functional importance disproportionate to their limited extent.

   Floodplain areas in the United States have undergone extensive land-use change over the past century (National Research Council 1992). Development frequently occurs in riparian areas because towns and cities have historically located there for convenience and trade. Extensive construction of levees and dams has

fundamentally altered the physical and ecological structure of floodplains, and has encouraged continued use of these landscapes for human use (Philippi 1996). As a result, floodplain forests have been reduced by 80% or more in many parts of the United States (Swift 1984, Noss et al. 1995, Schoenholtz et al. 2001), and in Wisconsin 1.8×10^6 ha (almost 50%) of wetlands were lost over the past 200 yr (Dahl 1990). The consequences of floodplain alteration may include degraded water quality (e.g., Osborne and Wiley 1988, Hunsaker and Levine 1995) and changes in both aquatic (Niemi et al. 1990) and terrestrial (Nilsson and Jansson 1995, Gergel et al. 2002) communities.

A handful of studies have explored the effects of floodplain land-cover change with respect to conservation (Poiani et al. 2000), stream restoration (Kauffman et al. 1997), tree recruitment (Miller et al. 1995), land-use planning and management (Hunsaker and Levine 1995), biodiversity and connectivity (Ward et al. 1999), and land–river interaction (Welcomme 1988). Most of these efforts have been restricted to relatively small floodplain areas and/or limited temporal extents or resolution. Therefore, the first objective of this study was to determine land-cover changes over ~309 km² of the Wisconsin River floodplain for a period of 60 yr. Specifically, we asked: How has the spatial distribution of land use and land cover in the floodplain of the Wisconsin River changed from the 1930s to the 1960s to the 1990s, both within the floodplain as a whole and also for the buffer zone along the river's edge?

An important aspect of land-use change is the change in connectivity, that is, the spatial continuity of a habitat or cover type across a landscape (Turner et al. 2001). Functionally, habitat connectivity influences the ease with which organisms or materials traverse the landscape between adjacent ecological units or land-cover patches (Ward et al. 1999), and intact vegetation patches are especially important for many birds (Hansen and Urban 1992) and mammals (Gottfried 1979). Within floodplains, benefits of forest connectivity include provision of species habitat and movement corridors (Knutson and Klaas 1998), enhanced species diversity (Naiman et al. 1993), as well as protection of water quality (Brunet and Astin 1997) and soil biogeochemical activities (Brown et al. 1997). Therefore, we addressed a second question: How has habitat connectivity, especially for forested land cover, changed over the past 60 yr in the Wisconsin River floodplain landscape?

Recent studies have identified the need for greater synthesis of ecological research and land management (e.g., Dale et al. 2000; Turner et al. 2002), and more evaluation of ecological dynamics in areas of mixed ownership (Pearson et al. 1999), but the means to accomplish this are still being developed. Our final objective was to ask how various conservation scenarios based on forest management agendas would influence
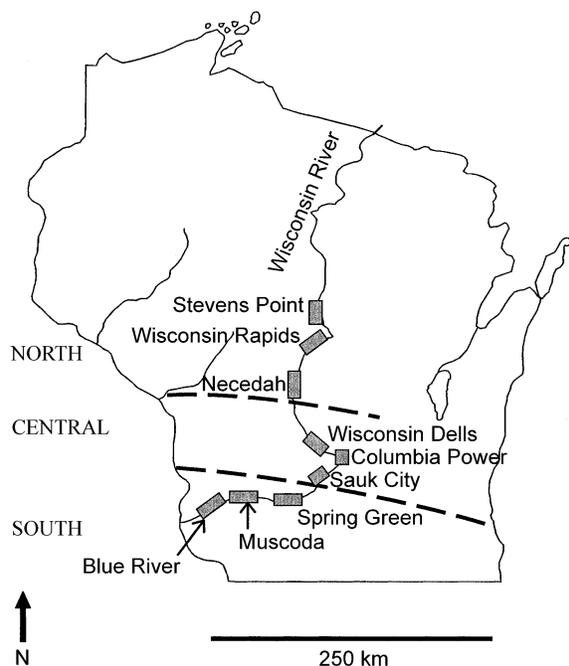

Fig. 1. Location of study reaches and delineation of three study regions along the Wisconsin River, Wisconsin, USA. See Table 1 for study reach characteristics.

forest connectivity within the Wisconsin River floodplain. These scenarios were motivated by real-world resource management goals of reducing non point-source pollution at the patch scale and improving wildlife habitat at the landscape scale, as well as the availability of floodplain land due to farm failures.

STUDY AREA

The Wisconsin River flows ~700 km from its source in northern Wisconsin to its confluence with the Mississippi River and falls 328 m, draining an area of 31 440 km² across 25 counties. Our study region included the spatial extent of 100-yr floods and focused on the lower half of the river from Stevens Point to the confluence 370 km downstream (Fig. 1). Nine 12–21-km-long study reaches were located throughout the study area, grouped into northern, central, and southern regions (Table 1) based on location and similarities in geology, topography, and flow modifications. Reaches were distributed as evenly as possible within each region, while avoiding areas of major urban riverbank development, slackwater and/or reservoirs, and dams. The nine reaches in this study varied in length and width, with the largest reach (Wisconsin Dells) >5 times the area of the smallest reach (Muscoda).

Presettlement vegetation in the Wisconsin River watershed was dominated by oak savanna, with pine barrens of jack pine (*Pinus banksiana*) more prevalent to the north, and southern mesic forest (of sugar maple *Acer saccharum*, basswood *Tilia americana*, and American elm *Ulmus americana*) to the south. Patches

TABLE 1. Characteristics of the nine study reaches along the southern Wisconsin River, ordered from upstream to downstream.

Reach	Length (km)	Area (km²)	km_D†
North			
Stevens Point	12	17.4	355
Wisconsin Rapids	15	20.0	329
Necedah	20	32.6	223
Central			
Wisconsin Dells	21	106.0	178
Columbia Power	14	31.2	165
Sauk City	17	53.2	118
South			
Spring Green	18	32.0	88
Muscoda	12	18.0	56
Blue River	16	27.6	40

† Distance (in km) from the downstream end of the reach to the confluence with Mississippi River = km_D.

of sedge meadow and prairie occurred throughout the watershed as well (Curtis 1959).

The northern study region falls within a section of the state dominated by low relief sand plains and sandstone buttes. From Stevens Point down to the Wisconsin Dells reach, the river is essentially a sequence of privately owned hydropower dams and large ''flowages'' (reservoirs), several of which were built after 1930. Mean annual flow in this region is 143 m³/s at Wisconsin Rapids.

In the central region, dams are less frequent as the river passes through sand plains and hills that inspired Aldo Leopold's classic book *A Sand County Almanac,* and the quartzite-dominated Baraboo Hills area. This section of the river contains a discontinuous series of river-edge and setback levees, especially within the Wisconsin Dells reach. Levee construction began as early as 1890, but most structures were built between 1910 and 1920. Mean annual discharge is 198 m³/s at Wisconsin Dells, and although there are fewer dams than in the northern study region, the cumulative impact of levees and multiple upstream impoundments significantly alters the hydrologic regime in this section of the river (Gergel 2002).

The southern region begins downstream of the last dam on the Wisconsin River, and the remaining 148 km to the Mississippi River comprise the 32 000 ha Lower Wisconsin State Riverway (LWSR). The LWSR is a popular recreational resource receiving >400 000 visitor-days annually (WDNR 1988), and management priorities are based primarily on maintaining aesthetic attributes of the river. The southern reaches (Spring Green, Muscoda, Blue River) fall entirely within the LWSR, and contain large amounts of protected Wisconsin Department of Natural Resources (WDNR) forest, state wildlife management areas, and several state parks. In this southern region the river traverses mixed dolomite, sandstone, and limestone hills of the ungla-

ciated ''Driftless'' region of the state. Mean annual discharge is 248 m³/s at Muscoda.

Rates of population increase from 1937 to 1990 in counties surrounding the river varied from 12% in the south, to 107% in the central, to 68% in the northern region. Three small cities (population 18 000–38 000) are located directly on the Wisconsin River (Wisconsin Department of Administration 2000).

METHODS

Land-cover mapping

To evaluate land-cover changes, three spatial data sets were developed based on the interpretation of orthocorrected aerial photographs. Coverages were produced for each of the nine reaches, representing three time periods: the 1930s, 1960s, and 1990s. All data were projected into Universal Transverse Mercator (UTM), Zone 16, using the 1983 adjustment to the North American Datum, with pixels of 1-m resolution.

The base land-cover layers for the 1930s and 1960s data sets were derived from 1:20 000 scale (generally ~23 × 23 cm [9 × 9 inch] format) historic aerial photos generated by mapping projects at the United States Department of Agriculture Soil Conservation Service. Missing photos were ordered from the U.S. National Archives and Records Administration or the Wisconsin State Department of Transportation. Depending on image availability, the actual dates for 1930s photos included 1937, 1938, and 1940, while the 1960s photos included 1965, 1967, and 1968. All photos were taken during leaf-on conditions from May through October.

To correct for scale differences, camera tilt, and relief distortions found in a normal aerial photograph (Lillesand and Kiefer 1994), we converted all images to orthophotos, allowing direct measurements of area and distance. Photos were scanned using a flatbed scanner at 700 dpi, then imported into the OrthoMapper (Image Processing Software, Madison, Wisconsin, USA) application (Scarpace et al. 2000) where registration and orthocorrection occurred. Camera position was calculated by registering the location of each image's fiducial marks, then ''visual orientation'' was accomplished by selecting known control points on a modern base orthophoto and selecting that same point with precision on the historic aerial photo. The most favorable points for this process were road intersections where relocation through time was least likely, and which usually presented well on the low contrast 1930s photos. Finally, the software ''draped'' each registered historic photo over a USGS Digital Elevation Model (DEM), obtained the coordinates for each control point from both the base and the historic images, and determined the best least squares solution to the final image. We used 70-m DEMs because 30-m DEMs were not available for all study reaches. The resulting individual orthophotos were then automatically overlaid to create a contiguous mosaic image using points that oc-

TABLE 2. Land-cover classification used in interpretation of aerial photos from the 1930s, 1960s, and 1990s.

Cover type	Classification rule
Deciduous forest	Area covered by woody perennial plants, with crown closure >10%, where canopy shows a predominance of trees or large shrubs
Coniferous forest	Area covered by woody perennial plants, with crown closure >10%, where majority of canopy is trees
Agriculture	Land under apparent cultivation and maintenance, which may or may not be planted in visible rows; includes pasture and harvested (i.e., bare) fields
Grassland	Land covered by noncultivated, herbaceous vegetation predominated by grasses, but including shrubs/patchy trees/savanna, with canopy cover <10%; if consistently >10%, area is considered forest
Water	Area covered by water, and with no vegetation present; river islands are digitized as separate features only if >100 m wide and not all sand; small water bodies surrounded by wetland are delineated but considered wetland
Open wetlands	An area with clear wetland drainage patterning, or with water below, at, or above the land surface long enough to be capable of supporting obvious wetland vegetation, and with <10% tree or shrub cover
Sand and/or barren land	Land with little or no plant presence or other cover, but not including minor, all-sand islands (which are not classified)
Urban	Significant urban development, including major highways and interstates, small subdivisions, and suburbs; but not including isolated occurrences of farm buildings, homesteads, warehouses, minor or secondary roads

curred in the overlap between adjacent photos to produce one black and white orthoreferenced land-cover image for each study reach, with 1-m pixel resolution. Analyses of the software accuracy have been conducted at the University of Wisconsin–Madison using root mean square error determination (Kruepke 2000).

Land-cover layers for the 1990s were derived from digital orthophotos acquired from the USGS, individual county land offices, commercial mapping providers, and other sources. Actual dates of origin for photos ranged from 1994 to 2000, and all were created from leaf-on imagery. Files were reprojected into the UTM system; then individual photos were clipped and combined to produce one complete black and white orthoreferenced image per reach, also with 1-m pixel resolution.

One hundred year floodplain delineations were derived from maps produced by the Federal Emergency Management Agency, National Flood Insurance Program. The limit of the 100-yr flood was transcribed to USGS 7.5-min topographic quads, and digitized using a high precision tablet digitizer and the ArcEdit module within Arc/Info versions 7.9 and 8.0 (ESRI 1992).

Interpretation of land cover was done using the on-screen digitizing capability of ArcView version 3.2 GIS (ESRI 1992). The minimum mapping unit for any land-cover polygon was 1 ha. Polygons were classified using set rules that divided land cover into one of nine discrete cover classes (Table 2). Following classification, each coverage was independently double checked for gaps or overlapping polygons, rasterized at 50-m pixel resolution, then exported as ASCII files for landscape metric calculation.

Landscape analysis

Measures of the extent of each cover type for the entire reach and immediately adjacent to the river cor-ridor, and gaps in forest cover adjacent to the river, were acquired directly from ArcView (ESRI 1992). In addition, we used four landscape metrics, generated using FRAGSTATS software (McGarigal and Marks 1994): number of patches, mean patch size, patch density, and edge density. These metrics were selected to assess changes in connectivity of the four most common land-cover types (deciduous forest, agriculture, grassland, and open wetland), and for urban cover due to its potentially significant impacts. Higher connectivity is associated with a larger number of patches at a greater density, often with higher mean patch sizes and lower edge density. Lower connectivity is associated with fewer patches or a lower mean patch size, a lower patch density, and increases in edge density.

Trends in land cover immediately adjacent to the river (i.e., the riparian zone) were measured using a custom routine that converted the channel to one polygon (islands were removed), moved directly shorewards from that polygon, and determined the cover type along both banks. Forest gaps were counted each time the cover was not forest or water.

Landscape conservation scenarios

The third part of this study investigated the application of landscape ecology to floodplain land management, and we selected four reaches for scenario analysis. We excluded the southern region reaches because they fall fully within the protection of the Lower Wisconsin State Riverway, and thus have little development pressure and human intervention. To represent the northern geographic region of the study, we chose the Stevens Point and Wisconsin Rapids reaches, which have narrow floodplains and occur downstream of large reservoirs. To represent the central region, we chose the Wisconsin Dells and Sauk City reaches, which have

far wider floodplains, sandy channels, and are further away from large reservoirs.

Six scenarios were designed to reflect realistic conservation agendas within a given river reach, and results were assessed by their ability to increase floodplain forest connectivity. We explored alteration to the forested buffer in which gaps were filled (''B'' Scenarios), as well as reversion of farmland to forest (''R'' Scenarios). By ''buffer'' we mean the longitudinal band along the river's edge; in this part of the study, a ''gap'' denotes a space >100 m long in the forested buffer that is not occupied by forest, wetland or water, as these are all cover types that would likely be left unaltered by conservation projects. One of the most commonly recommended actions to enhance floodplain forest connectivity is to join all riparian forest patches by filling gaps (National Research Council 1992); that option is represented by the two buffer scenarios. The remaining four (reversion) scenarios reflect situations in which complete gap filling may not be socially or economically possible, and where land ownership, zoning, or agency jurisdiction make the establishment of long, interconnected patches unlikely (e.g., Wear and Bolstad 1998, Wright and Tanimoto 1998). In such situations, conservation efforts often must focus on land parcels dispersed across the floodplain, which we chose to represent by the conversion of farmland parcels to deciduous forest using the most patches and the least patches possible. For simplicity, the only criterion used to identify patches to be reverted was patch size, and factors such as patch location relative to levees or other patch types, were not taken into account for the reversion scenarios. The scenarios were

Buffer (B)   B50: fill all nonwater, nonwetland gaps in the riparian forest buffer to a distance of 50 m from the river
                 B100: fill all nonwater, nonwetland gaps in the riparian forest buffer to a distance of 100 m from the river

Reversion (R)   R5+: revert 5% of agricultural land using large (i.e., fewer) patches
                R20+: revert 20% of agricultural land using large patches
                R5−: revert 5% of agricultural land using small (i.e., more) patches.
                R20−: revert 20% of agricultural land using small patches

To avoid buffering lengthy side channels and tributaries with new forest in the buffer scenarios (B), a single polygon was created that represented only the main stem river (i.e., backwaters, sloughs, and tributary channels were severed, and islands were removed). All gaps in the forest bordering the river (except water and wetland) were then reclassified as polygons of deciduous forest to a distance of 50 m and 100 m from the river based on general recommendations for buffer strip

width (see Castelle et al. 1994; Fig. 2). Coverage layers for the four reversion scenarios (R) were created by choosing either the fewest or greatest number of distinct polygons to equal the desired land reversion percentage; these polygons were then manually reclassified (Fig. 2). All scenarios used exported ASCII files for analysis in FRAGSTATS (McGarigal and Marks 1994).

Conservation scenarios were evaluated by comparing the change in landscape structure to the initial 1990s cover. We measured the same four landscape metrics mentioned above (using FRAGSTATS), as well as the spatial extent of land cover. We also determined the number of individual landowners and multiple-owner ''small tract'' holdings (or subdivisions) whose land was targeted for conversion in each scenario. Ownership information was acquired manually by superimposing transparencies of landscape patches over printed county plat maps. Given that land and finances available for floodplain forest conservation are usually limited, we then use these assessments to explore the question of which landscape patches are the most important to focus on.

Results

Land-cover change

During the 1930s, deciduous forests and agriculture dominated the Wisconsin River floodplain, with wetlands and grasslands limited to <20% of the floodplain. Land-cover change over the ensuing 60 yr was characterized by increases in forest extent and decreases in agricultural and grassland areas in all three regions (Fig. 3). By the 1990s, deciduous forest covered the largest portion of every reach and represented ∼50% of floodplain area in all regions. More spatially specific information about the 60-yr trends can be gained by tracking individual landscape polygons through time. Virtually all the increase in forest cover was attributable to conversion of agriculture and grassland patches (Table 3). Forest gains resulted from approximately equal areas of grassland and agricultural land conversion in the north and south, whereas agricultural conversion alone was responsible for the majority of forest increase in the central region (Table 3). Open wetlands declined in the north but increased in the central region and more than doubled in extent in the southern region. Grassland declined more than any other land cover from 1937 to 1990; by 1990, grasslands had declined by >67% in all three regions. Finally, while the extent of urban areas was extremely limited (<2% for all reaches), the northern, central, and to a lesser degree, the southern region, experienced large relative increases in this cover type between the 1930s and 1990s (Fig. 3).

Trends along the banks of the main stem channel differed from those for the floodplain as a whole. Forest cover was more prevalent along the river edge than

Buffer scenarios (B)

Reversion scenarios (R)

Fewer larger patches
(R5+ and R20+)
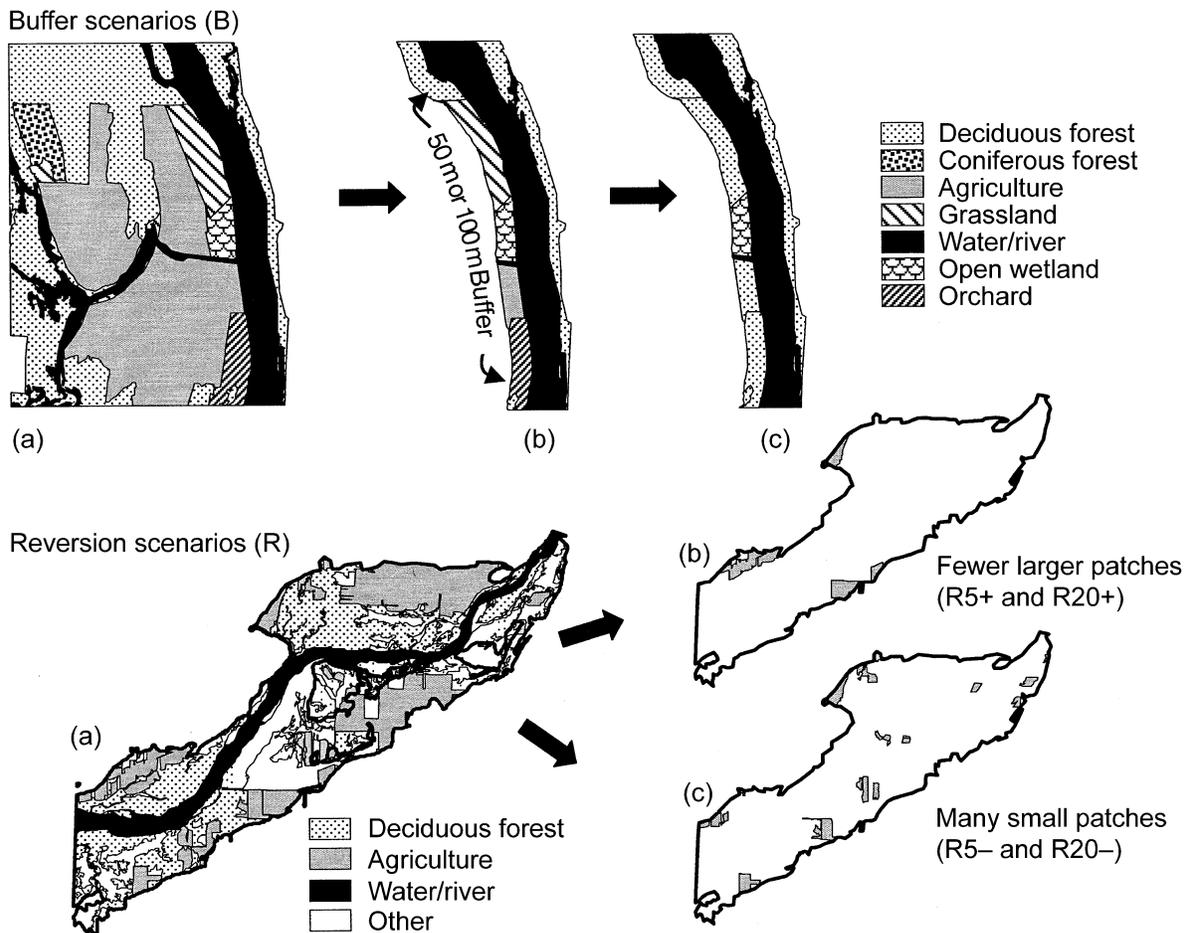
Many small patches
(R5− and R20−)

FIG. 2. Depiction of representative procedures for conservation scenarios. (Top panels) Buffer scenarios B50 and B100: (a) A portion of a typical floodplain landscape with several different land-cover types. (b) Within the larger floodplain, a 50-m and a 100 m deep buffer parallel to the riverbank is delineated. In this depiction, a buffer is shown only on the left side of the river; (c) All land cover in the buffer is converted to deciduous forest, except wetland and water categories. The converted buffer is then merged back into the preexisting land cover for the entire reach (not shown). (Bottom panels) Agricultural reversion scenarios R5+, R20+, R5−, and R20−: (a) An entire reach is depicted, with agricultural and forest land covers highlighted. (b) The R5+ and R20+ options use largest (i.e., few large patches are reverted) patches to achieve the scenario goal of reverting 5% or 20% of agricultural land, respectively. (c) The R5− and R20− options use smallest patches (i.e., many small patches are reverted) to achieve the scenario goal of reverting 5% or 20% of agricultural land. The selected patches are converted to deciduous forest and then merged back into the preexisting land cover for the entire reach (not shown).

across the entire floodplain; the length of channel bordered by deciduous forest has been ≥74% for all three regions since 1937, increasing modestly to a mean of 77–89% for all regions in the 1990s (Fig. 4). The most consistently decreasing land use bordering the river was agriculture, while trends in river edge open wetland, grassland, and urban areas were highly variable (Fig. 4).

Changes in land-cover connectivity

We plotted mean patch size against patch density for each cover type to determine changes in connectivity over time (Fig. 5). Deciduous forest cover became distributed in a smaller number of larger patches in all three regions whereas temporal changes in connectivity

of open wetland differed among the three regions. The decline in total wetland area in the north (see Fig. 3) was associated with a decrease in patch size but not in patch density. The increased extent of total wetland area in the central region was associated with an increase in patch density, but little change in mean size of wetland patches. In contrast, wetland patches increased in both size and density in the south. Agricultural patches decreased in both size and density in the northern and southern regions, whereas patch size decreased substantially with little change in patch density in the central region. Grassland tended toward both smaller patches and lower densities in all three regions. This transition occurred in stages: a reduction in mean patch size but with a concurrent increase in patch den-
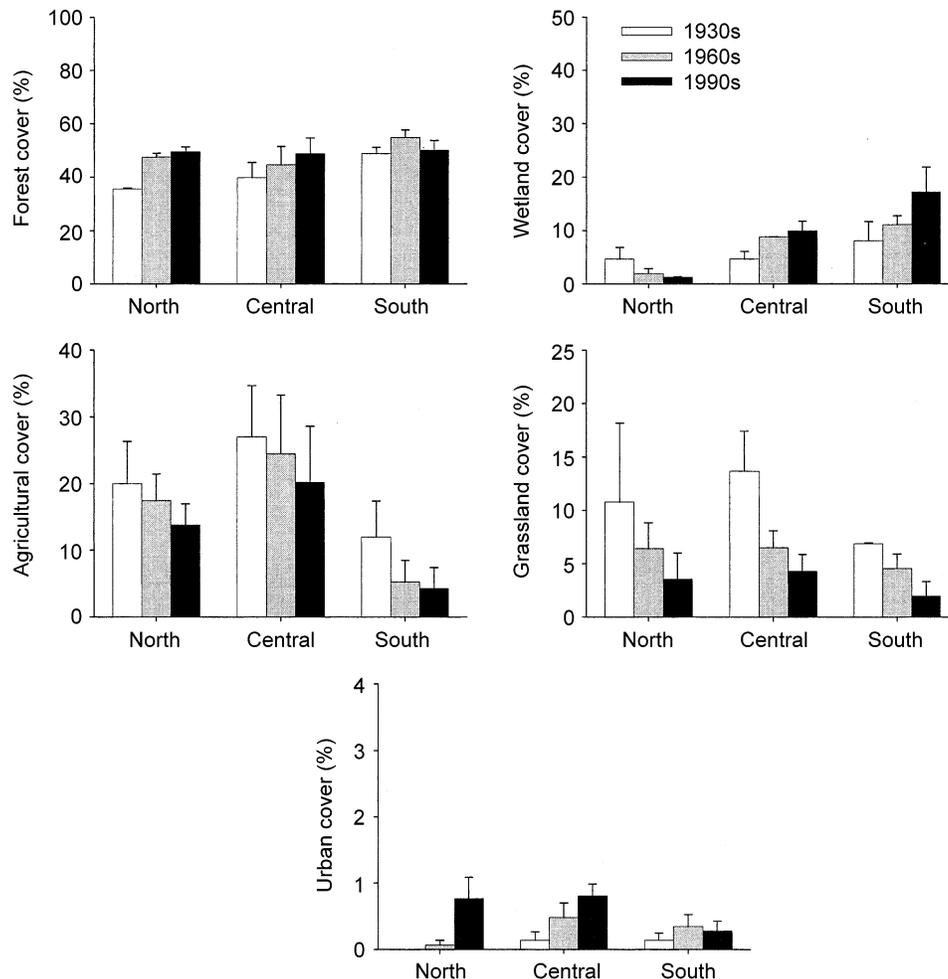
FIG. 3. Mean percentage of the floodplain landscape occupied by deciduous forest, open wetland, agriculture, grassland, and urban land covers in the 1930s, 1960s, and 1990s in the three study regions. Error bars represent +1 SE. Note differences in y-axis scales.

sity between 1930 and 1960 (particularly in the northern and southern regions), followed by a decline in patch density with little change in mean patch size from 1960 to 1990 (Fig. 5). This general pattern suggests that large grassland patches first became divided into several small patches, followed by the conversion of these smaller patches to some other cover type. Concomitant declines in edge density also were apparent for both agriculture and grassland, while mean forest edge density increased over time in all regions and eight out of nine study reaches. Open wetland edges decreased in the north, increased in the central region, and did not change in the south (Fig. 6).

Physical gaps in forest cover, especially in buffer areas, are an effective way to explore connectivity within the riparian zone. The number of gaps in the riparian forest edge, the total length of gaps, and the gap density (number of gaps/km of river edge) remained relatively consistent over time for all regions, although there was a modest decline in the percent of shore in gaps for the southern region between the 1930s and 1990s (Table 4).

Conservation scenarios

Two types of conservation scenarios, buffer (B) and reversion (R), explored the effect of management agendas within four selected river reaches. In the two buffer scenarios, each reach began with 7–10% of all floodplain forest contained within the 50-m buffer, and 13–18% within the 100-m buffer. The B50 treatment typically generated results approximately half the magnitude of the B100 treatment (except in the case of landowners involved; Table 5); thus we focus only on the latter scenario for simplicity.

In the two northern reaches (Stevens Point and Wisconsin Rapids), the B100 scenario increased forest cover within the buffer zone by 37.6% and 25.7%, and by 6.5% and 6.1% for each entire reach, respectively. Although these changes affected <3% of the total reach area, buffer conversion increased the forest mean patch

TABLE 3. Area and number of polygons that changed from agriculture or grassland in the 1930s to forest for the nine study reaches along the Wisconsin River.

Reach	1930s agriculture converted to 1990s forest		1930s grassland converted to 1990s forest		Total gain of forest 1930s to 1990s	
	Area (ha)	Polygons (no.)	Area (ha)	Polygons (no.)	Area (ha)	Percentage of reach
Stevens Point	41	32	187	59	228	13.1
Wisconsin Rapids	101	25	117	27	218	10.9
Necedah	301	55	6	8	307	9.4
Wisconsin Dells	878	110	489	91	1367	12.9
Columbia Power	218	28	133	34	351	11.3
Sauk City	281	47	259	32	541	10.2
Spring Green	167	43	45	14	212	6.6
Muscoda	32	20	76	14	108	6.0
Blue River	64	18	144	19	208	7.5

size by ~3 ha (25%) in the Stevens Point reach, and ~11 ha (71%) in the Wisconsin Rapids reach. In the two central reaches (Wisconsin Dells and Sauk City), the B100 conversion led to markedly smaller forest cover increases of only 7.3% and 14.2% for the riparian buffer and 1.1% and 1.9% for the entire reach. Forest mean patch size increased by only 2.1 ha (7%) in Wisconsin Dells and 0.4 ha (<1%) in Sauk City. Despite
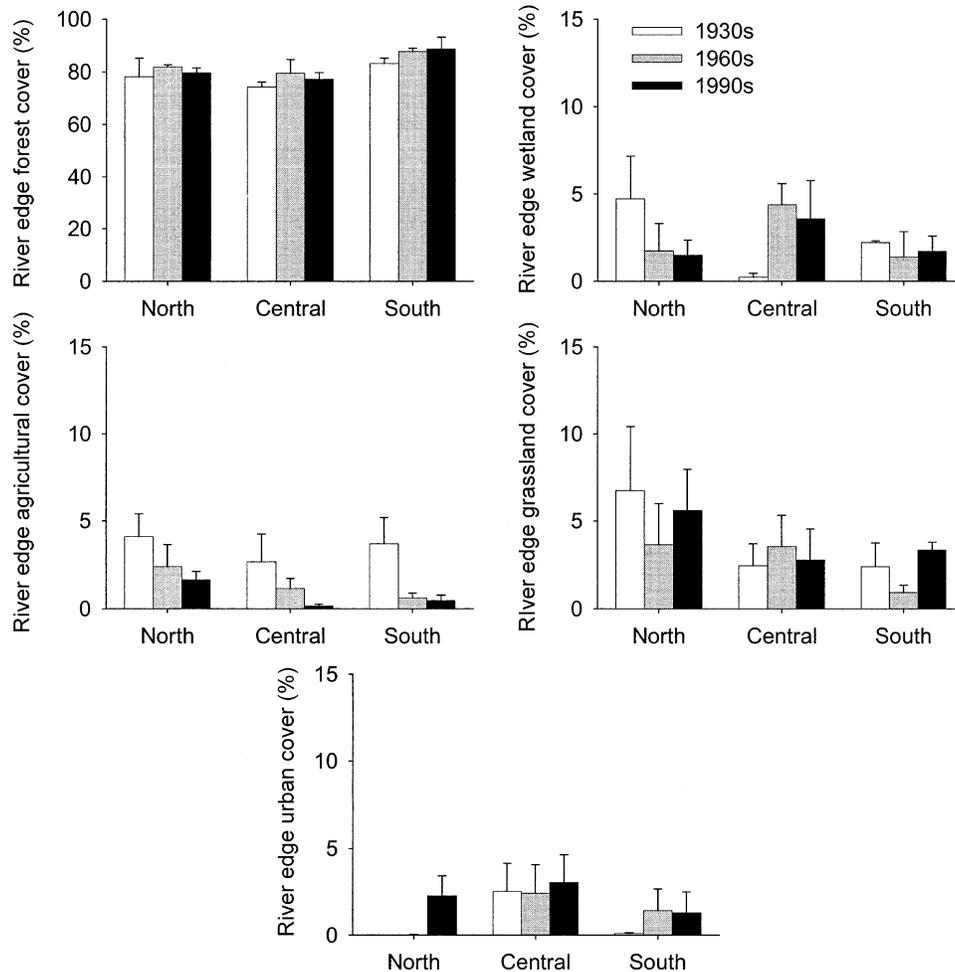

FIG. 4. Mean percent land cover of the five major cover types immediately adjacent to the main stem river in the 1930s, 1960s, and 1990s. Error bars represent +1 SE. Note differences in *y*-axes.
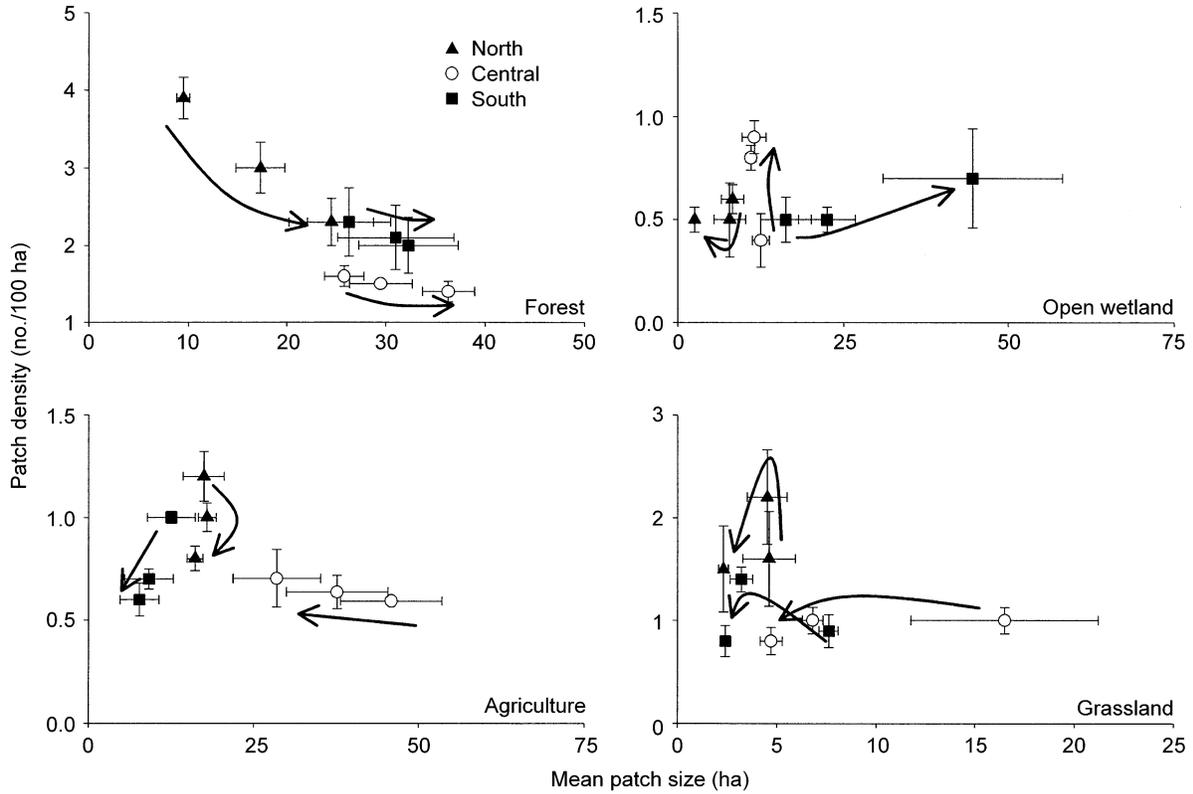
FIG. 5. Changes in spatial arrangement of the four major cover types in North, Central, and South regions over time. Region-averaged mean patch size is plotted against mean patch density for deciduous forest, open wetland, agriculture, and grassland. Error bars represent ±1 SE. Arrows trace the trajectory of change from the 1930s to the 1990s within each study region. Note differences in *x*- and *y*-axis ranges.
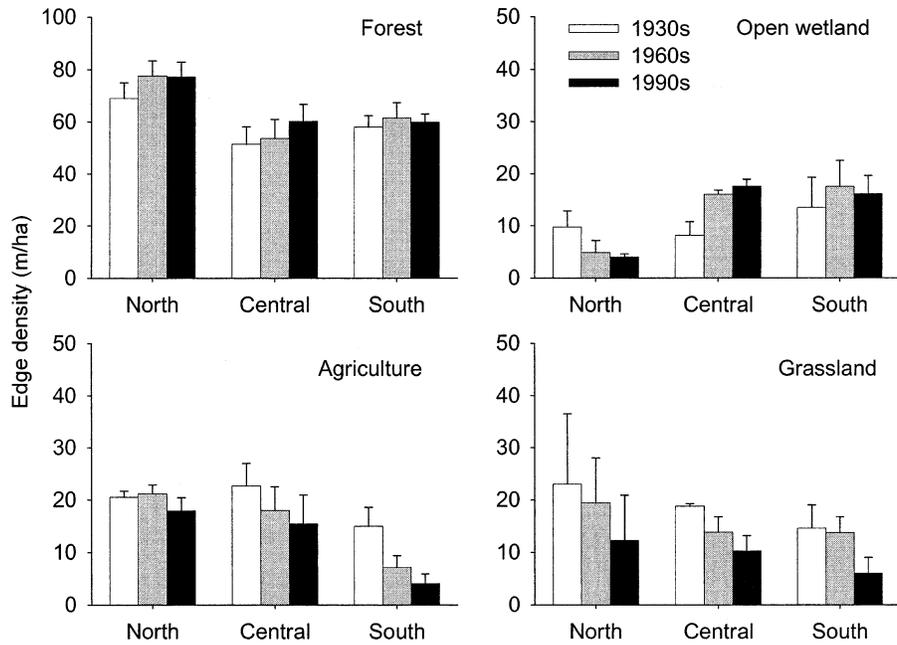

FIG. 6. Mean edge density for four major land-cover types by region in the 1930s, 1960s, and 1990s. Error bars represent +1 SE.

TABLE 4. Mean number of forest gaps adjacent to the main stem river channel and percentage of shoreline in non-forest cover through time in the Wisconsin River floodplain.

Region	Year	Gaps in forest (no.)	Total shore length (km)	Gap density (no./km)	Percent of shore in gaps
North	1937	16 (2.4)	31 (5.4)	0.5 (0.09)	15.9 (3.84)
	1968	22 (11.1)	32 (5.5)	0.6 (0.21)	12.5 (2.95)
	1990	21 (8.4)	32 (5.2)	0.6 (0.14)	13.8 (3.86)
Central	1937	16 (4.1)	36 (4.1)	0.4 (0.06)	21.9 (1.62)
	1968	24 (11.9)	36 (4.4)	0.6 (0.25)	17.7 (5.41)
	1990	17 (5.5)	37 (4.3)	0.4 (0.13)	19.9 (2.04)
South	1937	14 (2.9)	30 (2.6)	0.4 (0.06)	15.0 (2.25)
	1968	12 (1.3)	30 (3.2)	0.4 (0.01)	9.4 (0.71)
	1990	12 (4.6)	30 (2.8)	0.4 (0.12)	8.4 (3.75)

Notes: Total shore length = the length of main channel along both sides of the river. Islands were excluded, and backwaters and tributaries were severed for calculations. Values in parentheses are 1 SE.

the differing responses in connectivity between northern and central reaches, a similar number of gaps were filled and landowners were affected in all reaches (Table 5).

Four alternative scenarios (R) of reverting patches of agricultural land were also applied to the two northern and two central reaches (Table 6). In comparison to the buffer scenarios, the R5+ and R5− treatments produced relatively small increases in each of the connectivity metrics and involved far fewer landowners. Because the difference between using a few large patches (R5+) and many small patches (R5−) was min-

imal for the 5% conversion treatment, we focus on the R20 scenario.

Under the R20+ scenario, the two central reaches experienced notable increases in forest cover whereas changes in the two northern reaches were nominal. Forest cover increased 3.4% and 2.3% in Stevens Point and Wisconsin Rapids, and forest mean patch size increased 16.8% (2.2 ha) and 6.7% (1.3 ha), respectively (Table 6). Only two individual landowners were involved. However, in the central reaches (Wisconsin Dells and Sauk City), agriculture reversion produced forest mean patch size increases of 39% (11.7 ha) and

TABLE 5. Configuration of forest patches in the Wisconsin River floodplain in the 1990s and after imposing conservation scenarios in which non-forested riparian buffer areas were converted to forest.

Measure	Stevens Point		Wisconsin Rapids		Wisconsin Dells		Sauk City	
	1990s	After treatment	1990s	After treatment	1990s	After treatment	1990s	After treatment
B50								
Patches (no.)	61	57	47	36	136	130	50	52
Mean patch size (ha)	13.0	14.3	15.7	20.8	31.3	32.8	46.0	45.1
Patch density (no./100 ha)	3.5	3.3	2.4	1.8	1.3	1.2	0.9	1.0
Edge density (m/ha)	86.1	91.9	58.8	60.4	52.8	53.2	47.7	50.9
Gaps filled (no.)		22		15		20		17
New forest cover (ha)		22.0		16.4		24.8		24.2
Increase in buffer forest (%)		27.2		16.4		5.6		14.6
Percent of reach affected		1.3		0.8		0.2		0.5
Increase in total forest (%)		2.8		2.2		0.6		1.1
Landowners involved (no.)		10		12		13		12
Small tracts involved (no.)		3		5		4		5
B100								
Patches (no.)	61	52	47	29	136	129	50	51
Mean patch size (ha)	13.0	16.3	15.7	26.9	31.1	33.2	46.0	46.4
Patch density (no./100 ha)	3.5	3.0	2.4	1.5	1.3	1.2	0.9	1.0
Edge density (m/ha)	86.1	90.4	58.8	58.5	52.8	52.8	47.7	50.3
Gaps filled (no.)		27		24		28		22
New forest cover (ha)		51.3		45		45.5		42.8
Increase in buffer forest (%)		37.6		25.7		7.3		14.2
Percent of reach affected		2.9		2.3		0.4		0.8
Increase in total forest (%)		6.5		6.1		1.1		1.9
Landowners involved (no.)		14		21		21		15
Small tracts involved (no.)		3		6		6		6

Note: Scenarios involved filling all non-forest gaps (except water and wetland) in existing forest buffer along the mainstem channel to a depth of 50 m (B50) or 100 m (B100).

TABLE 6. Configuration of forest patches in the Wisconsin River floodplain in the 1990s and after imposing conservation scenarios in which agricultural lands were reverted to forest.

Measure	Stevens Point			Wisconsin Rapids			Wisconsin Dells			Sauk City		
	1990s	R+	R−	1990s	R+	R−	1990s	R+	R−	1990s	R+	R−
R5												
Patches (no.)	61	64	67	50	49	47	150	143	130	56	55	51
Mean patch size (ha)	13.1	12.8	12.2	19.3	20.1	21.0	30.1	32.7	36.0	41.7	43.7	47.1
Patch density (no./100 ha)	3.5	3.7	3.8	2.5	2.5	2.4	1.4	1.4	1.2	1.1	1.0	1.0
Edge density (m/ha)	87.0	83.9	85.0	77.3	75.7	75.9	55.5	55.5	54.7	50.3	49.8	49.6
Forest cover (%)	45.8	47.0		48.3	49.5		42.5	44.1		43.9	45.2	
New forest cover (ha)		12			8			168			67	
Percent reach affected		0.7			0.4			1.6			1.3	
Increase in total forest (%)		1.3			1.1			1.6			1.3	
Landowners involved (no.)		2	4		2	1		13	33		10	17
Small tracts involved (no.)		0	0		0	1		0	1		0	1
R20												
Patches (no.)	61	56	59	50	49	46	150	124	109	56	51	49
Mean patch size (ha)	13.1	15.3	14.5	19.3	20.6	22.0	30.1	41.8	47.6	41.7	51.0	53.1
Patch density (no./100 ha)	3.5	3.2	3.4	2.5	2.5	2.3	1.4	1.2	1.0	1.1	1.0	0.9
Edge density (m/ha)	87.0	83.2	83.8	77.3	75.2	74.0	55.5	54.6	52.8	50.3	49.4	47.6
Forest cover (%)	45.8	49.2		48.3	50.7		42.5	48.9		43.9	48.9	
New forest cover (ha)		50			33			674			268	
Percent reach affected		2.9			1.7			6.3			5.0	
Increase in total forest (%)		3.4			2.3			6.4			5.0	
Landowners involved (no.)		2	8		2	6		30	67		14	32
Small tracts involved (no.)		1	1		0	1		1	3		1	1

Note: Scenarios involved transformation of 5% (R5) or 20% (R20) of agricultural land to deciduous forest using few large patches (R+) or many small patches (R−).

22% (9.3 ha), respectively. Thirty landowners in the Dells reach and 14 in the Sauk City reach were involved.

Under the contrasting R20− scenario, forest conversion was accomplished by using many small patches. Because the same amount of land was converted to forest, metrics relating to forest cover (percent forest cover, new forest cover, percent reach affected, and percent increase in total forest) were identical for both the R+ and R− scenarios. As in the previous R20+ scenario, the central reaches showed greater forest connectivity increases than the two northern reaches for the R20− treatment. For the northern sites, the amount of change in forest mean patch size caused by the R20− treatment (10.7% and 14.0%) was similar to changes from the R20+ conversion, but involved more landowners (Table 6). In the Wisconsin Dells, forest mean patch size for the R20− treatment increased by 58% (compared to 39% for the R20+ treatment), and in the Sauk City reach, it produced an increase of 27% (vs. 22% for R20+). However, the number of landowners affected was appreciably higher: 67 and 32 landowners were involved in Wisconsin Dells and Sauk City, respectively.

DISCUSSION

Changes in land-cover percentage and distribution

The arrangement and extent of land cover in the Wisconsin River floodplain has changed since the 1930s. While trends were often divergent among the three study regions, common patterns included increased extent of deciduous forest and declines in grassland and agricultural cover. One striking attribute of the Wisconsin River floodplain landscape is the amount, persistence, and general increase of deciduous forest over the 60-yr study period despite marked increases in population densities in most reaches (ICPSR 1972, Wisconsin Department of Administration 2000). However, forest cover was not distributed uniformly within individual reaches; for every region the proportion of land in forest was greater along the river edge than across the entire 100-yr floodplain. Increasing forest cover in the floodplain stands in strong contrast to longer term (>200 yr) patterns for other large river floodplain systems (Décamps et al. 1988, Knutson and Klaas 1998, USGS 1999) and to statewide trends. In Wisconsin, forest lands have declined significantly since the 1950s (Mauldin and Plantinga 1999), often resulting in smaller, more isolated patches with increased edge : area ratios (Sharpe et al. 1987). The causes for divergent trends between uplands and the floodplain are not immediately obvious, but may reflect growing awareness of both the unsuitability of these latter environments for residential land use and the environmental and social value of intact floodplain ecosystems.

Changes in absolute amount of grassland cover were accompanied by very large reductions in mean patch size in all but one reach, and decreasing patch numbers and densities. Collectively, these trends demonstrate that grasslands are becoming rarer and now occur mostly as small, widely dispersed patches. In upland areas,

such trends have been attributed to successional dynamics that followed abandonment of agricultural lands and the suppression of fire required to maintain native prairie (Andersen et al. 1996, Leach and Givnish 1996), and we suspect that similar processes are also occurring in lowland floodplains of the state (Bürgi and Turner 2002).

Agriculture noticeably declined in most reaches, usually a result of a shift toward a smaller number of smaller land holdings. Declining agricultural land cover and patch size in the floodplain is reflective of a larger statewide trend, in part driven by economic pressures on family farms in Wisconsin (Olmstead 1997). Many rural areas are witnessing suburban sprawl, and the conversion of farms to housing subdivisions causes increases in land taxes, forcing the retirement of historic farming parcels (Andersen et al. 1996, Daniels and Bowers 1997).

Wetland patch dynamics demonstrated complex and divergent spatial and temporal patterns along the Wisconsin River. Decreasing wetland area in the northern region contrasted increases in the central and southern regions. Declines in the north reflected reductions in the size of individual wetland patches, and may have resulted from damming and flow regulation in this region, which could reduce the extent of saturated soil areas and allow forest establishment (Miller et al. 1995). Before human manipulation, seasonal pulses in this region were probably capable of entirely inundating the rather narrow floodplain, whereas dams make the current flow relatively uniform, trapping the river in the main stem channel and leaving wetlands hydrologically unsustained. In the central region, increased wetland area was associated with gains in the total number of wetland patches over the 60-yr period, whereas greater wetland area in the south reflected an increase in both the number and mean size of wetlands. Draining of wetlands has a long history in the Midwest (Rhoads et al. 1999), and in the 1930s aerial photos, agricultural fields were often visible in low-lying areas that may have been historic wetland. Many of these parcels were marginal for farming and reverted to wetter conditions upon abandonment in the 1930s or early 1940s (Prince 1995). Re-emergence of open wetlands along the Wisconsin River is also a result of resource management practices, particularly in the southern region where water levels in many floodplain areas are currently maintained at artificially high and relatively constant levels for fish and waterfowl production in the Lower Wisconsin State Riverway, giving rise to extensive "wetland reservoirs."

Urban land use increased over the past 60 yr in eight of the nine reaches, and individual urban patches often doubled or tripled in size. By the 1990s, up to 6% of the river edge was urban. Because our study was bounded by the 100-yr floodplain, and reaches were selected to avoid large urban centers (see *Study area*), urbanization was not extensive (<2% of all reaches). None-

theless, almost every reach has a town or small city adjacent to the channel, and often a large highway bridge (which we considered urban) or power line crossing the river. This seemingly moderate increase is likely to have a pronounced effect on the river given the disproportionately large influence of urban areas on nutrient runoff (Osborne and Wiley 1988, Detenbeck et al. 1993) and aquatic habitat quality (Wang et al. 1997).

Trends in land-cover connectivity

Changes in agriculture and grasslands in the floodplain were consistent with increasing loss and fragmentation of those cover types in almost all reaches. In contrast, gains in total amount and mean patch size, and declines in patch number that occurred in most reaches at first might suggest a shift toward greater connectivity for deciduous forest cover. However, forest edge density increased for all but one reach from 1937 to 1990, indicating that the larger patches are more complex in shape and crenulated along their edges—particularly in the north where mean edge density was often 10–20 m/ha greater than in the central and southern regions. Consequently, ecological benefits associated with increases in forest connectivity may be tempered by development of complex patch shape. For example, while bird species richness is often correlated with forest patch size (e.g., Freemark and Merriam 1986), greater edge density can increase susceptibility of interior-dwelling bird species to nest predation (Paton 1994) or parasitism by the brown-headed cowbird (*Molothrus ater*; Krummel et al. 1987). Similarly, in a study of forest fragments in south-central Wisconsin, Temple (1986) found that 16 bird species were sensitive to fragmentation within 100 m of the patch edge, and that successful breeding for interior species occurred only in patches with "core" habitat remaining. Thus the functional implications of the trend toward larger but more geometrically complex patches are not obvious.

Connectivity of open wetland increased in the southern region, decreased in the north, and despite an increase in total wetland area did not change substantially in the central region of the Wisconsin River. We did not consider wetland connectivity to have changed in the central region because the observed increase in total wetland extent was due to the addition of more wetland patches, which were relatively small and complex in shape (as indicated by an increasing edge density), over time. In contrast, the increased extent of wetland cover in the south did increase wetland connectivity because cover change was associated with an increasing number and size of wetland patches. This may reflect greater attention paid to wetland management in the more southerly reaches or a greater amount of regulatory protection (such as the existence of the Lower Wisconsin State Riverway). Other causes include the acquisition of property by the U.S. Fish and Wildlife

ROSS E. FREEMAN ET AL.

Service for rearing habitat, recent efforts by the U.S. Natural Resources Conservation Service (formerly Soil Conservation Service) to assist farmers in locating and protecting wetlands on their farm land, and the passage of critical legislation, such as the amended 1982 Clean Water Act (known for the ''Section 404'' wetland permits) or the closure of loopholes in ''dredge and fill'' permitted under the ''swampbuster'' provision of the 1985 Farm Bill (Mitsch and Gosselink 1993). The Natural Resources Conservation Service now also purchases and holds easements on agricultural land that was former wetland under its Wetlands Reserve Program.

Management for forest connectivity

Floodplain forests are important for many species and processes (Naiman and Décamps 1997), and connectivity of these areas is critical to maintaining ecosystem services (Brown et al. 1997). For example, patches of deciduous forest in river bottomlands can reduce sediment and nutrient transport; in particular when they are arranged as continuous buffers along the riverbank (Peterjohn and Correll 1984, Osborne and Kovacic 1993). And while it may be precarious to assign greater conservation or management value to one patch type over another, most ongoing floodplain restoration and management efforts focus on re-establishment of forests (Peterken and Hughes 1995, Schoenholtz et al. 2001) because of both ecological benefits and financial and logistic feasibility (Gren et al. 1995, Brown et al. 1997). At the same time, increasing connectivity of riparian and floodplain areas is also a primary restoration goal (e.g., Harris and Olson 1997, Russell et al. 1997). Thus we explored how forest connectivity changed as a result of several different land conversion scenarios aimed at increasing forest cover.

Perhaps the simplest conservation option for improving floodplain forest connectivity is to institute continuous buffers along the entire river corridor (buffer scenarios, B). This approach entailed reestablishing forest in all gaps that do not contain water, wetland, or urban cover (since its conversion was not considered practical). The B100 treatment greatly improved forest connectivity in the two northern reaches: longitudinal connectivity was enhanced and forest mean patch size increased dramatically when a 100-m buffer was established along both banks for the length of the reach. For example, by changing only 2.3% of the 2000-ha Wisconsin Rapids reach, we increased floodplain forest by >6%, raised forest mean patch size by 71%, and thus boosted forest connectivity substantially. However, improvements in forest connectivity were less pronounced in the two central reaches, where mean patch size increases were <7%. Further, such conservation scenarios would require negotiations with up to 21 different landowners and six small-tract parcels per reach. Small-tract parcels often signal the presence of a housing subdivision, reflect higher land prices due to

development infrastructure, and have frequent turnover such that locating actual current, legal owners is difficult. Thus, practical constraints could present expensive and possibly insurmountable challenges to forest restoration projects. If a 50-m buffer rather than the 100-m buffer is used, only 15 gaps (affecting only 0.8% of the reach) must be filled in the Wisconsin Rapids reach. This results in a 2.2% increase in total forest, but only 12 landowners would be affected.

Because filling all gaps in the riparian buffer will often not be feasible, other more incremental plans that focus on individual parcels must be considered. We addressed this need with the four alternative scenarios (R) by reverting 5% and 20% of the floodplain land area currently in agricultural use to deciduous forest. The low reversion treatment (5%) is less than the decline in agricultural land cover over 60 yr for all but one reach, while the higher treatment (20%) is approximately half of the average decline in agriculture for all nine reaches.

The scenarios involving reversion of agriculture (i.e., R5 and R20) produced outcomes distinct from buffer scenarios. While the buffer-filling scenarios resulted in marked increases in forest connectivity in the northern reaches, and little change in the central reaches, reversion scenarios had the opposite effect. That is, the connectivity increases were greatest in the central reaches and minimal in the north. Under the R20+ treatment, total forest cover in the Wisconsin Dells reach increased by 6.4% if 20% of agricultural land was reverted. The increase in forest mean patch size was less than that in the Wisconsin Rapids B100 scenario (39% for R20+ in Wisconsin Dells vs. the 71% increase for B100 in Wisconsin Rapids). More landowners would be involved (30 vs. 21), but only one small-tract holding occurred.

The second pair of reversion scenarios, in which we reverted the same amounts of land in each reach, but using many small patches (i.e., R5− and R20−), may be the conservation scenario closest to management realities. Often, land conservation is opportunistic and the financial resources of conservation groups or state management agencies are such that only a few, smaller purchases per year might be feasible. Purchases of larger, contiguous patches, as modeled in scenarios R5+ and R20+, are generally uncommon. The small patch treatments (R−) generated larger increases in forest mean patch size than the large patch (R+) treatments, but the trade-off occurred with the number of landowners involved (e.g., 67 in the Wisconsin Dells R20− scenario). Such smaller agricultural reversions might be more economically viable, but the widespread distribution of the land parcels might render management, stewardship, and monitoring of restored properties more labor intensive and expensive.

Each scenario had strengths and challenges, depending on the balance between current landscape structure and the societal feasibility and economics of each plan.

The most effective conservation scenario in one region was notably ineffective in the other (e.g., buffer filling resulted in substantial forest connectivity increases in the northern, but little change in central reaches). Conversely, agricultural reversion caused the greatest increase in mean patch size in the central region but little change in the north. The two northern reaches had forest buffers that were interrupted mainly by thin slivers of other land use along the river, so that filling in these few remaining forest gaps allowed large amounts of forest to become connected. In contrast, the two central reaches had many more gaps in the river edge forest, but also many gaps elsewhere in the forest cover and much wider floodplains, so that filling in the many river-edge gaps was not enough to substantially increase overall forest patch size for the entire reach. Beyond these gains in floodplain forest connectivity, the number of landowners affected by different management scenarios represents a critical constraint on idealized conservation plans. Filling buffer gaps might be the most obvious conservation choice, but is severely challenged by the number of landowners and small tracts involved. The option of reverting agricultural land on a piecemeal basis (i.e., conversion of several small parcels) generated less sizable improvements, and involved greater numbers of landowners, but these scenarios may be more economically viable due to their incremental approach.

CONCLUSION

For the Wisconsin River floodplain landscape, deciduous floodplain forest cover has slowly increased since the 1930s at the expense of agriculture and grassland cover, and overall gains in forest extent have been characterized by development of larger, geometrically complex patches. Declines in agriculture and grassland areas and increases in open wetland cover depict a 60-yr history of expansion, contraction, and spatial rearrangement of landscape patches. These trends underscore a complicated and dynamic pattern of landscape change over a relatively short temporal scale, and emphasize the need to explore how various management strategies might encourage or hinder this change (Naiman and Turner 2000).

Scenarios can depict future management options for agencies, conservationists, and private individuals. Our six scenarios yielded three interesting results: first, the different conservation strategies we implemented on these real floodplain landscapes led to similar optimum outcomes in terms of connectivity metrics—such as increases in the mean size of forest patch or amount of forest cover—but not for the same reach. For example, the buffer scenarios (B100) increased mean forest patch size by 25–71% in two northern reaches, while the entirely different reversion scenarios (R20) led to almost the same increases (22–58%) in two central reaches. Second, scenario outcomes were dependent on the spatial arrangement of the land-cover patches at the start of the scenario. Third, the metric of land ownership added a very practical facet to the scenarios. The most impressive increases in forest connectivity under the buffer scenarios involved from 14 to 21 different landowners, whereas the greatest increases under the reversion scenarios affected from 14 (using several large agricultural parcels) to 67 (using many small parcels) landowners. Clearly, the way that floodplain forest conservation occurs is just as significant as how much land is actually protected and the ideal management option must be tailored to the specific land-cover arrangements of a given river reach. There is a strong need to produce science that is not only rigorous, but which can also easily be used by land managers and conservationists (see Lubchenco 1998). Any sustainable management plan must also address social and economic factors (Naiman et al. 1995). Given that the literature is clear on the benefits of reducing fragmentation and enhancing forest connectivity (Saunders et al. 1991), it would seem prudent to use scenarios based on real landscapes in future large river floodplain research to assess various management regimes.

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