

Changes in aquatic vegetation and floodplain land cover in the Upper Mississippi and Illinois rivers (1989–2000–2010)

Nathan R. De Jager · Jason J. Rohweder

Received: 23 August 2016 / Accepted: 9 January 2017 / Published online: 24 January 2017
© Springer International Publishing Switzerland (outside the USA) 2017

Abstract Quantifying changes in the cover of river-floodplain systems can provide important insights into the processes that structure these landscapes as well as the potential consequences to the ecosystem services they provide. We examined net changes in 13 different aquatic and floodplain land cover classes using photo interpreted maps of the navigable portions of the Upper Mississippi River (UMR, above the confluence with the Ohio River) and Illinois River from 1989 to 2000 and from 2000 to 2010. We detected net decreases in vegetated aquatic area in nearly all river reaches from 1989 to 2000. The only river reaches that experienced a subsequent recovery of vegetated aquatic area from 2000 to 2010 were located in the northern portion of the UMR (above navigation pool 14) and two reaches in the Illinois River. Changes on the floodplain were dominated by urban development, which increased in nearly every river reach studied from 1989 to 2000. Agricultural lands declined in most river reaches from 2000 to 2010. The loss of agricultural land cover in the northern UMR was accompanied by increases in forest cover, whereas in the lower UMR and Illinois River, declines in agriculture were accompanied by increases in forest and shallow marsh communities. The changes in aquatic vegetation occupied between 5 and 20% of the total aquatic area and are likely associated with

previously reported regional improvements in water clarity, while smaller (1–15% of the total floodplain area) changes in anthropogenic land cover types on the floodplain are likely driven by broad-scale socio-economic conditions.

Keywords Aquatic ecology · Floodplain · Forest · Habitat · Land cover change · Submerged aquatic vegetation

Introduction

River-floodplains are diverse and dynamic landscapes that support regionally unique sets of ecosystem functions and services (Schindler et al. 2014). These systems are corridors for the migration of a variety of aquatic and terrestrial species (Naimen et al. 1993). Nutrients and sediments also move into and through these systems, and in some instances, river-floodplains can buffer downstream and coastal areas against eutrophication (Venterink et al. 2006). Hence, these systems have a relatively high capacity to provide ecosystem services related to clean water, recreational opportunities, and commercial harvest. Spatial and temporal changes in the cover of aquatic and floodplain areas can provide a first approximation of locations and trends in such ecosystem services because various cover classes differ in their ability to support different species and ecosystem functions (Tomaselli et al. 2013; Felipe-Lucia and Comín 2015). Changes in the cover of river-floodplain systems can also provide insights into the primary

N. R. De Jager (✉) · J. J. Rohweder
U.S. Geological Survey, Upper Midwest Environmental Sciences
Center, La Crosse, WI 54603, USA
e-mail: ndejager@usgs.gov

drivers that structure them, which is important for developing effective policies and strategies for restoring degraded river systems.

This study documents changes in the cover of aquatic and floodplain areas of the Upper Mississippi and Illinois rivers and their floodplains, collectively referred to as the Upper Mississippi River System (UMRS). Although heavily impacted by navigation infrastructure and anthropogenic floodplain land use, the UMRS continues to serve as the primary route for North American migratory waterfowl and passerines (Beatty et al. 2015; Fink et al. 2010). In addition, the UMRS is home to an estimated 140 fish species, some of which are commercially harvested, while others provide sport fishing opportunities (Garvey et al. 2010). The UMR is also a major conduit to the Gulf of Mexico, and some lentic and floodplain areas have a relatively high potential for denitrification (Strauss et al. 2011), which could help to reduce Gulf hypoxia in some years. Hence, the importance of the UMRS extends well beyond the physical boundary of the ecosystem. Given the broader importance of the UMRS, efforts to establish management and restoration policies and strategies that consider the primary agents of change within the system should also have broader importance.

The distribution of primary aquatic and land cover types in the UMRS has been well studied (WEST Consultants, Inc. 2000; Theiling et al. 2000; De Jager et al. 2011). Low head dams are used to raise water levels during low flow periods in the northern river reaches. This specific change has altered the character of the northern UMR from a braided channel network with abundant floodplain forests to large reservoir-like areas that generally support open water and marsh habitats just above each lock and dam (WEST Consultants, Inc. 2000; Theiling et al. 2000). Lower in the river system, wing dams and other channel training structures are used to concentrate flow and scour the main channel. Levees are further used to isolate the floodplain from the river and these levees are associated with a decrease in public land and increase in agricultural land use as one moves south along the floodplain (WEST Consultants, Inc. 2000; Theiling et al. 2000). A recent study further examined changes in land cover from 1975 to 1989 and 2000 across the entire UMR and found that contemporary changes were minor relative to the above historical changes (De Jager et al. 2013), suggesting that navigation, flood protection infrastructure, and human land use continue to be the main drivers of patterns in river-floodplain cover.

Despite our understanding of long-term and large-scale changes in the cover of the UMRS, a number of questions about the location and magnitude of more contemporary changes in both the river and floodplain remain unanswered. For example, during the early 1990s, strong declines in aquatic vegetation were observed in portions of the northern UMR and were linked to the occurrence of drought, decreased water levels, and low light transparency (Rogers 1994; Fischer and Claflin 1995). Subsequent recovery of aquatic vegetation has been noted in some portions of the northern UMR (Popp et al. 2014; De Jager and Yin 2010) and in the upper portions of the Illinois River (Sass et al. 2010), occurring as early as 2003. In contrast, reaches lower in these rivers are suggested to have never had much aquatic vegetation or not recovered from the crash in the 1990s (Yin et al. 2002; Cook and McClelland 2007; MACTEC Engineering and Consulting 2006; Sass et al. 2010). Clarifying the locations and scales across which such changes occurred is important because aquatic vegetation is a keystone component of the impounded portions of the UMRS (Korschgen et al. 1988).

Similar questions concern locations and magnitudes of contemporary change within the floodplain of the UMRS. For example, forest cover is the dominant vegetation type along the entire course of the floodplain (De Jager et al. 2013). There is widespread concern among resource managers that hydrological impacts associated with navigation infrastructure and expansion of agricultural and urban land use will continue to reduce forest cover throughout the river system, especially with the arrival of highly competitive exotic herbaceous wetland species such as *Phalaris arundinacea* (reed canary grass) (Guyon et al. 2012). Depending on which cover classes forest loss is associated with, such losses could result in a reduced capacity of the floodplain to sequester sediments and nutrients, less habitat for avian and other species, and a general loss of biodiversity. However, no study has examined the degree to which such changes are occurring within the UMRS. In the present study, we use remotely sensed data as a way to identify the locations and magnitudes of change in aquatic vegetation and floodplain land cover across the entire river system from 1989 to 2000 and from 2000 to 2010, thereby helping to better quantify contemporary changes and identify some potential causes and consequences of those changes.

Methods

Study area

This study documents changes in the navigable portions of the Upper Mississippi River (UMR) and Illinois River and their floodplains (Fig. 1). These two rivers are often divided into a series of navigation reaches, with dams at their downstream ends. For this study, the UMR was divided into 24 navigation reaches, one tributary reach (St. Croix, *stc*) and two undammed open river reaches (*or1* and *or2*; Fig. 1). The Illinois River was divided into eight navigation reaches (Fig. 1). Throughout this study, we refer to these areas as navigation reaches and we summarized the composition of

aquatic and floodplain cover as well as net changes among time periods at these spatial extents.

Data sources

We obtained geospatial data layers from the Long-Term Resource Monitoring element of the Upper Mississippi River Restoration Program (<http://www.umesc.usgs.gov/ltrmp.html>) for the years 1989, 2000, and 2010/2011. These datasets were developed through interpretation of aerial imagery. The same thematic classification scheme (Table 1) was applied to each set of photos. The classification system was developed specifically for the Upper Mississippi River System and is a blend of traditional land cover and land use

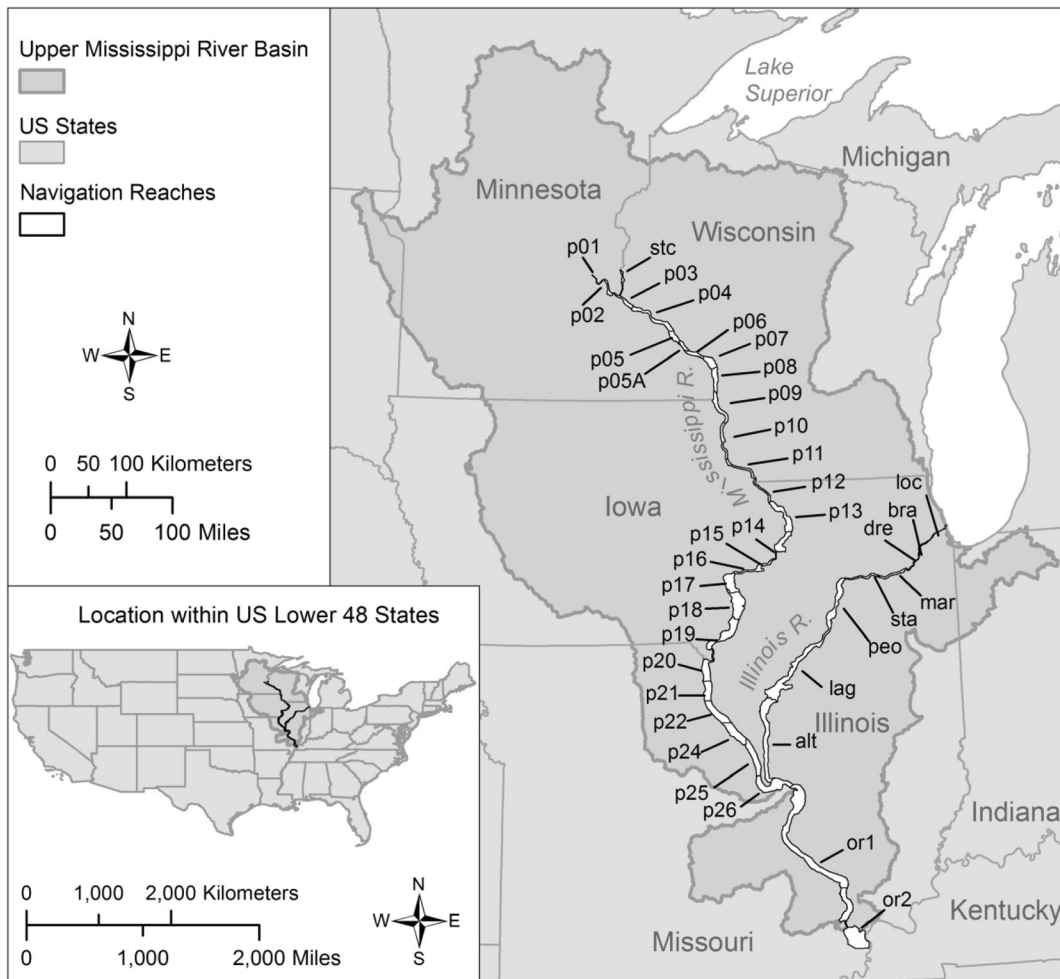


Fig. 1 This study examined aquatic and floodplain cover change within a series of navigation reaches of the Upper Mississippi and Illinois rivers. The Upper Mississippi River was divided into 24

navigation reaches, one tributary reach (St. Croix, *stc*) and two undammed open river reaches (*or1* and *or2*). The Illinois River was divided into eight

classes (e.g., roads, developed areas, agriculture) and aquatic and wetland vegetation classes (Dieck et al. 2015). Aquatic and wetland vegetation classes were delineated similarly to the Cowardin classification system (Cowardin et al. 1979), but see Dieck et al. (2015) for complete details.

Aerial photography was collected from August to September during the typical “low-water” time period on the UMRS. Low-water conditions occurred for all of the navigation reaches mapped in 1989 and 2000 and for the navigation reaches north of p14 on the UMR and for the Alton to Marseilles reaches of the Illinois River in 2010. However, high water conditions occurred for the remainder of the river system during 2010, and thus, photography was collected for the remaining reaches during 2011. In 2011, water levels were still higher than those observed during either 1989 or 2000, but photography was collected on the remaining reaches regardless. Water levels ranged from 0.3 to 0.87 m higher for these reaches in August and September of 2011 than they were during the same months in 1989 and 2000. These higher water levels can influence the ability to detect certain vegetation classes, such as herbaceous aquatic and wetland plant communities as well as agricultural areas which can become completely submerged during high water. However, photo interpretation takes this into account where possible. For example, if the species typically classified as shallow, deep marsh, or wet meadow are observable but below the water surface, they are still classified as they would have been if water levels were lower. Similarly, flooded agricultural lands are still classified as agricultural lands where there is no obvious land cover change.

Each dataset was developed independently of the other datasets with imagery that varied from one time to the next. In 1989, 1:15,000 scale color infrared aerial photos were used and polygonal features were interpreted and delineated at a 0.4-ha minimum mapping unit. A similar methodology was employed in 2000; 1:24,000 scale color infrared aerial photos were used with a 1-ha minimum mapping unit. However, the 2010/2011 imagery was collected with a digital camera at 0.2 m per pixel for navigation reaches 1–13 on the Upper Mississippi River and 0.4 m per pixel in the remainder of the river system. These resolutions are

equivalent to 1:406 and 1:812, respectively. Although the resolution of the imagery collected in 2010/2011 was much greater than that in 2000 and 1989, features were still delineated using a minimum mapping unit of 0.4 ha for navigation reaches 1–13 of the Upper Mississippi River and 1 ha for the other reaches in order to better compare images across time. In general, the methods used in 1989 and 2000 were much more similar to each other than to the methods used in 2010. Thus, unidirectional changes in aquatic and floodplain land cover could be confounded by changes in methodology.

An accuracy assessment was conducted for two navigation reaches for the data from 2010 (Jakusz et al. 2016). Using the 31 classes in Table 1, the overall pool-wide accuracy ranged between 76 and 82%. However, several individual classes were difficult to distinguish from each other and often had accuracies that fell below 60%. We therefore used the 15-class classification, which generally performed better with an overall accuracy from 82 to 88%. However, the wet meadow class was often difficult to distinguish from the shallow marsh class and we therefore grouped them. In addition, initial analyses showed large changes from wet forest to upland forest from 1989 to 2000 and then back to wet forest in 2010. We interpreted these changes to be due to difficulty in distinguishing among forest types in the early datasets, and we therefore grouped upland and wet forest into a single “forest” class (Table 1).

Even after grouping classes to achieve a conservative classification system, the differences in image resolution and quality need to be taken into account when interpreting the results of this and other studies that seek to compare navigation reaches spatially and over time. Because of these differences, we focused our efforts on quantifying net changes across relatively broad spatial extents (navigation reaches) rather than attempting to track pixel-level transitions as is traditionally done in land cover change analyses. The implication of this is that potentially important transitions among land cover classes could be masked by the broader net changes in cover classes. However, net changes are still valuable because they can reveal overall trajectories of cover change, which is the focus of this study.

Data analysis

We isolated changes that took place within aquatic areas from those that took place within floodplain areas to more directly connect such changes with causal

Table 1 Various classifications for aquatic and floodplain cover types in the Upper Mississippi River System along with descriptions and species present

Class type	13 Class	15 Class	31 Class	Description/species present
Aquatic	Deep marsh	Deep marsh	Deep marsh annual	<i>Zizania aquatica</i>
	Deep marsh	Deep marsh	Deep marsh perennial	<i>Sagittaria latifolia</i> , <i>Sagittaria rigida</i> , <i>Sparganium eurycarpum</i> , <i>Typha angustifolia</i> , <i>Typha latifolia</i> , <i>Pontederia cordata</i>
	Open water	Open water	Open water	<10% vegetated water
	Rooted floating aquatics	Rooted floating Aquatics	Rooted floating aquatics	<i>Nelumbo lutea</i> , <i>Nymphaea</i> spp. <i>Nuphar</i> spp.
	Submersed aquatic vegetation	Submersed aquatic vegetation	Submersed aquatic vegetation	<i>Vallisneria americana</i> , <i>Elodea canadensis</i> , <i>Stuckenia pectinatus</i> , <i>Potamogeton</i> spp., <i>Ceratophyllum demersum</i>
Floodplain	Agriculture	Agriculture	Agriculture	Cultivated crops
	Developed	Developed	Developed	Manmade features, houses, dams
	Levee/roadside	Levee/roadside	Levee	Continuous dikes or embankments
	Levee/roadside	Levee/roadside	Roadside	Roads, highways, and railroads
	Sand/mud	Sand/mud	Mudflat	Non-vegetated mud near lakes, ponds, backwaters
	Sand/mud	Sand/mud	Sand	Dry non-vegetated sand
	Sand/mud	Sand/mud	Sandbar	Temporarily flooded unvegetated sand near main channel
	Grass/forbs	Grass/forbs	Grassland	<i>Bromus inermis</i> , <i>Phleum pratense</i> , <i>Poa pratensis</i> , <i>Andropogon gerardii</i> , <i>Panicum virgatum</i> , <i>Schizachyrium scoparium</i> , <i>Sorghastrum nutans</i>
	Grass/forbs	Grass/forbs	Pasture	Perennial grasses and forbs used for hay or livestock
	Shallow marsh	Wet meadow	Sedge meadow	<i>Carex stricta</i> , <i>Carex lacustris</i> , <i>Carex haydenii</i> , <i>Carex pellita</i> , <i>Carex vulpinoidea</i>
	Shallow marsh	Wet meadow	Wet meadow	<i>Phalaris arundinacea</i> , <i>Leersia oryzoides</i> , <i>Spartina pectinata</i> , <i>Panicum virgatum</i> , <i>Lycopus americanus</i> , <i>Vernonia fasciculata</i> , <i>Solidago canadensis</i> , <i>Solidago gigantea</i> , <i>Asclepias incarnata</i>
	Shallow marsh	Shallow marsh	Shallow marsh annual	<i>Echinochloa crus-galli</i> , <i>Echinochloa muricata</i> , <i>Bidens frondosa</i> , <i>Bidens cernua</i> , <i>Cyperus odoratus</i> , <i>Xanthium strumarium</i> , <i>Polygonum pennsylvanica</i> , <i>Eleocharis obtusa</i>
	Shallow marsh	Shallow marsh	Shallow marsh perennial	<i>Schoenoplectus fluviatilis</i> , <i>Phragmites australis</i> , <i>Polygonum amphibium</i> , <i>Lythrum salicaria</i>
	Forest	Upland forest	Upland forest	<i>Quercus rubra</i> , <i>Quercus alba</i> , <i>Carya ovata</i> , <i>Populus tremuloides</i> , <i>Betula papyrifera</i> , <i>Ulmus americana</i>
	Forest	Upland forest	Conifers	Non-actively managed conifers (<i>Pinus</i> spp., <i>Juniperus</i> spp.)
Forest	Upland forest	Plantation	Actively managed conifers	

Table 1 (continued)

Class type	13 Class	15 Class	31 Class	Description/species present
	Forest	Wet forest	Floodplain forest	<i>Acer saccharinum</i> , <i>Populus deltoides</i> , <i>Salix nigra</i> , <i>Betula nigra</i> , <i>U. americana</i>
	Forest	Wet forest	Lowland forest	<i>Quercus bicolor</i> , <i>Q. rubra</i> , <i>Quercus macrocarpa</i> , <i>B. nigra</i> , <i>Acer negundo</i> , <i>P. deltoides</i> , <i>Carya cordiformis</i>
	Forest	Wet forest	Populus community	<i>P. deltoides</i> >50% (other species listed in FF category at <50%)
	Forest	Wet forest	Salix community	<i>S. nigra</i> , <i>Salix interior</i>
	Shrub/scrub	Shrub/scrub	Shrub/scrub	<i>Amorpha fruticosa</i> , <i>Rhus hirta</i> , <i>Rhus glabra</i> , <i>Lonicera tatarica</i> , <i>Lonicera morrowii</i> , <i>Elaeagnus umbellata</i> ,
	Wet shrub	Wet shrub	Shallow marsh shrub	<i>Cephalanthus occidentalis</i> , <i>Decodon verticillatus</i> , <i>S. interior</i> , <i>Cornus amomum</i>
	Wet shrub	Wet shrub	Deep marsh shrub	<i>C. occidentalis</i> , <i>D. verticillatus</i>
	Wet shrub	Wet shrub	Wet meadow shrub	<i>S. interior</i> , <i>Amorpha fruticosa</i> , <i>C. amomum</i> , <i>Cornus sericea</i> , <i>Sambucus canadensis</i> , <i>Sambucus racemosa</i>

mechanisms that likely differ between the two components of the landscape. All aquatic classes were expressed as a percentage of the total aquatic area within a given navigation reach and time period, and all floodplain classes were expressed as a percentage of the total floodplain area for a given navigation reach and time period. This was done to standardize areas among navigation reaches with differing sizes. Net change over time was then calculated as the change in the above percentages. Given the larger number of floodplain classes, we conducted a multivariate analysis (principal components analysis with varimax rotation) on the proportion of the floodplain in different cover classes to characterize patterns in floodplain land cover and change among the three time periods. This analysis helped us to attribute spatial and temporal patterns in floodplain land cover to specific land cover classes. We used PCA biplots and loadings to identify correlations among cover classes, navigation reaches, and time periods and used changes in the location of individual reaches within the biplots from one time period to the next to detect and explain changes in land cover.

Results

Aquatic cover types

From 1989 to 2000, all but six of the navigation reaches of the Upper Mississippi River showed a net loss in the percentage of aquatic area in submerged aquatic vegetation and deep marsh and a net gain in unvegetated open water (Fig. 2). Changes in aquatic vegetation ranged from 5% of aquatic area in reaches with little change to approximately 20% of aquatic area in reaches with more change. The loss of submerged aquatic vegetation was strongest in the navigation reaches north of p20, where vegetation was initially more abundant in 1989 (Figs 2 and 3). In the Illinois River, the two most upstream navigation reaches saw an increase in submerged vegetation, while the lower reaches showed very little change (Figs. 2 and 3). From 2000 to 2010, the navigation reaches north of p14 on the Upper Mississippi River showed a net increase in submerged vegetation and deep marsh ranging from 5 to 25% of aquatic area, suggesting that these reaches rebounded from the decline in aquatic vegetation from 1989 to 2000. In contrast, the reaches south of p13 continued

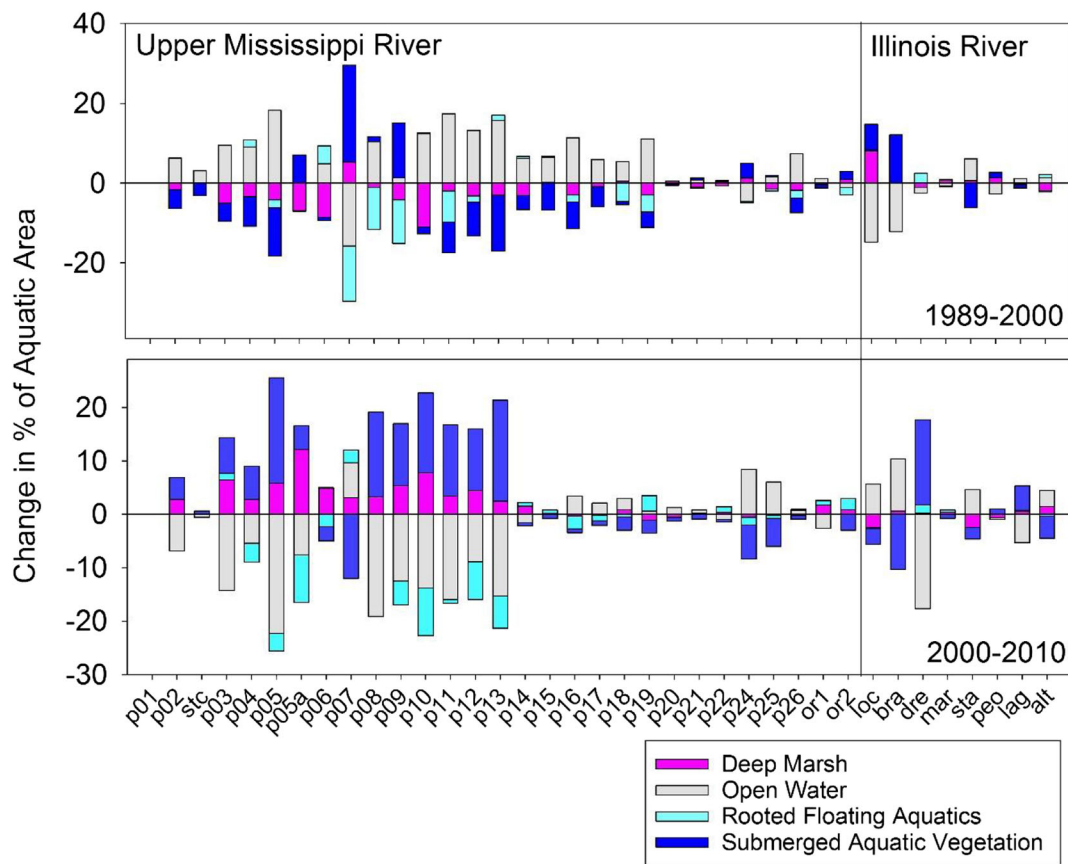


Fig. 2 Changes in aquatic areas for each navigation reach on the Upper Mississippi and Illinois rivers. Changes are expressed as a percentage of the total aquatic area of each reach at each time

to lose submerged aquatic vegetation and gain unvegetated open water. Mixed results were again found in the Illinois River, with some reaches gaining and others losing aquatic vegetation (Figs. 2 and 3). Despite differences in the direction and magnitude of the changes in aquatic vegetation among navigation reaches, the basic spatial structure of the river system has changed little over this 20-year time period, with relatively abundant aquatic vegetation in the northern portion of the system and much less vegetation lower in the system (Fig. 3). Navigation reach p8 (Fig. 4) illustrates the strong changes in aquatic vegetation representative of the northern reaches of the Upper Mississippi River.

Floodplain cover types

Relative to the net changes in aquatic vegetation, net changes in floodplain land cover were relatively

minor, typically occupying less than 10% of the floodplain. From 1989 to 2000, nearly all pools of both rivers showed a net gain in the percentage of the floodplain in developed area, ranging from 0 to 8% of floodplain area (Fig. 5). An exception was p13 of the Upper Mississippi River, which showed a large decline in developed area (~16% of floodplain area) and proportional increase in grassland area. However, visual inspection indicated that this change was due to a single large military installation, which was classified as developed in 1989 and grassland in 2000, despite relatively minor changes. Other classes that showed changes were agriculture, forest, and shallow marsh. However, there were no coherent patterns in such changes among collections of navigation pools. From 2000 to 2010, nearly all navigation pools showed a net increase in the percentage of the floodplain in forest cover (0–8% of floodplain area) and a proportional net decrease in the

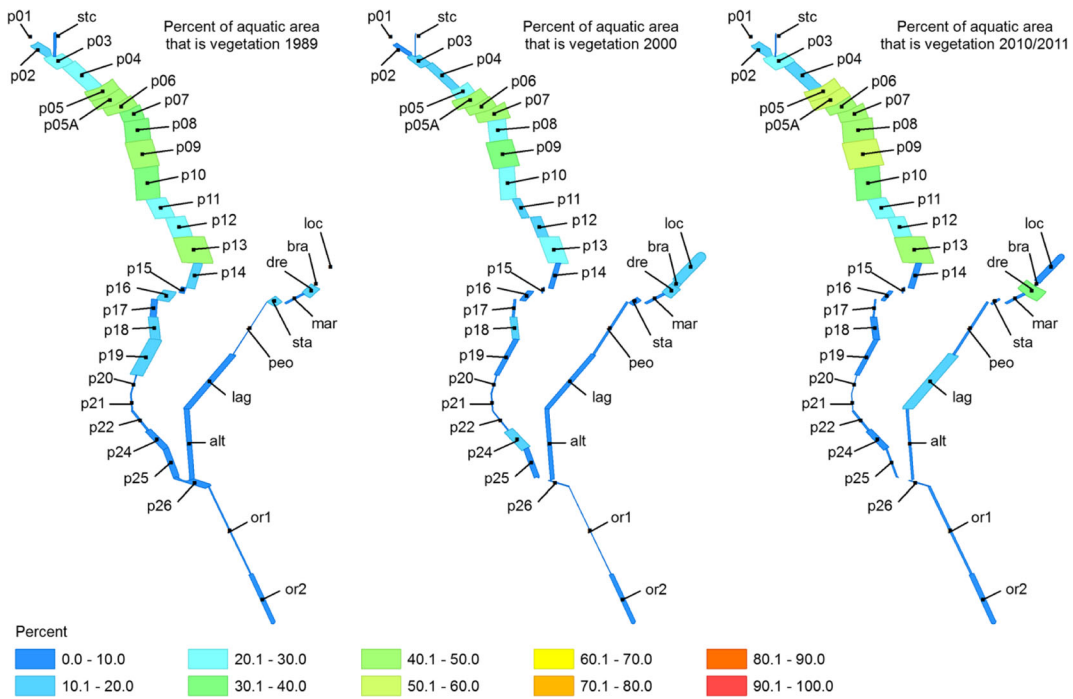


Fig. 3 Percentage of the total aquatic area in aquatic vegetation classes within each navigation reach of the Upper Mississippi and Illinois rivers for each time period

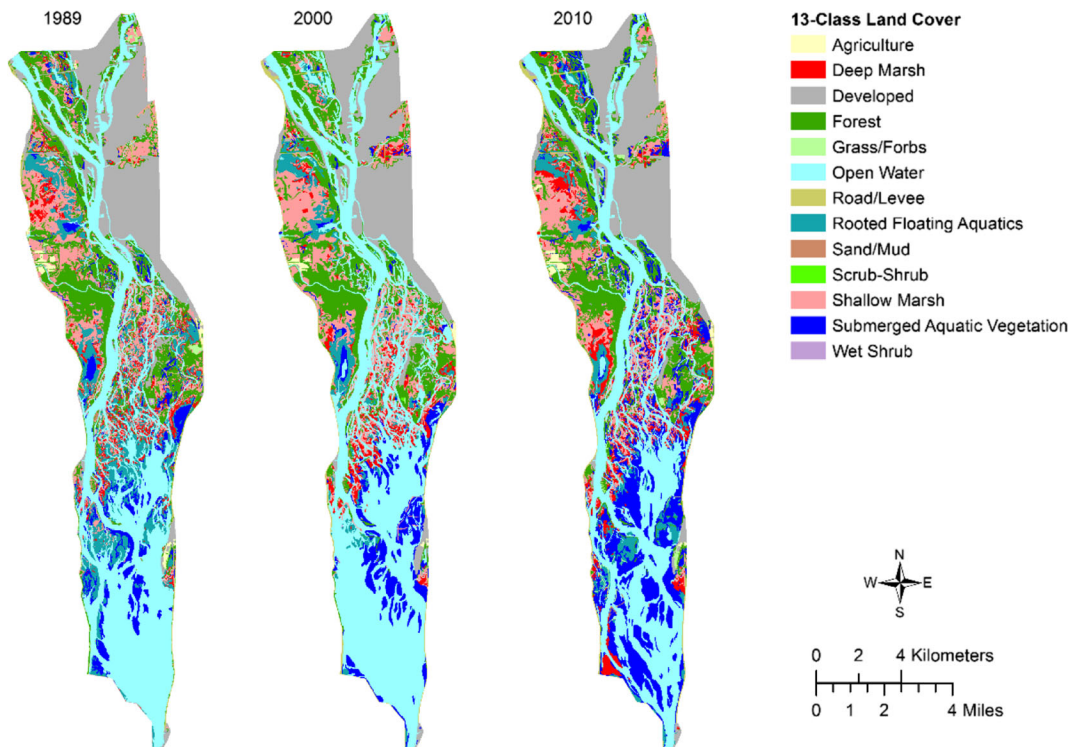


Fig. 4 Navigation reach p8 of the Upper Mississippi River is a good example of the initial decline and subsequent recovery of aquatic vegetation in the northern UMR from 1989 to 2000 and from 2000 to 2010, respectively

percentage of the floodplain in shallow marsh and agriculture (Fig. 5).

Multivariate analyses of the floodplain data for all reaches and time periods showed minor shifts in the land cover of some pools over time (Fig. 6). However, the basic spatial pattern across the river system remained relatively unchanged over this 20-year time period. The first principal axis accounted for 69.1% of the variation in land cover among reaches and time periods and was positively correlated with developed area ($r = 0.494$) and forest cover ($r = 0.244$) and negatively correlated with agriculture ($r = -0.830$). The second principal component accounted for an additional 28% of the variation in floodplain land cover and was positively correlated with shallow marsh ($r = 0.24$) and forest cover ($r = 0.64$) and negatively correlated with

agriculture ($r = -0.21$) and developed area ($r = -0.71$). All other floodplain cover classes had weak and non-significant associations with the different PCA axes ($r < 0.21$). The southern navigation reaches of the Upper Mississippi River showed a strong separation from the other navigation reaches along the first principal component axis, indicating dominance by agricultural land cover. The remaining reaches showed variation along the second principal component axis, suggesting variation in the degree to which they were dominated by forest and shallow marsh vegetation (upper portion of the biplot) or development (lower portion of the biplot). Minor shifts in land cover were noted along the second principal component for a number of navigation reaches from 1989 to 2000, reflecting increases in developed area, while minor shifts were noted along the first

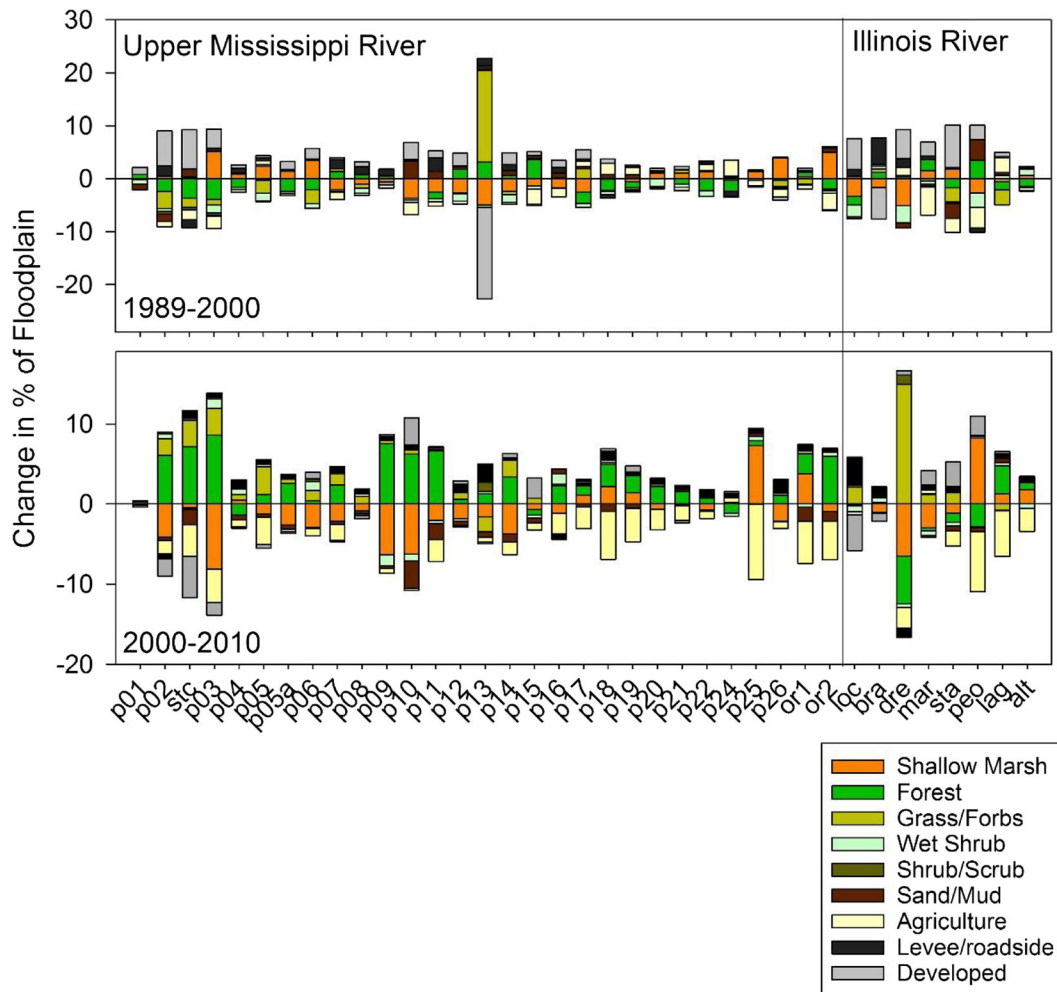


Fig. 5 Changes in floodplain classes for each navigation reach on the Upper Mississippi and Illinois rivers. Changes are expressed as a percentage of the total floodplain area of each reach at each time period

principal axis from 2000 to 2010, reflecting decreases in agricultural land cover (Fig. 6). Navigation reach p25 (Fig. 7) illustrates the changes in agricultural land cover observed in many of the southern navigation reaches of the Upper Mississippi River.

Discussion

Our analyses in the Upper Mississippi and Illinois rivers and floodplains from 1989 to 2010 revealed strong differences in the composition of aquatic and floodplain areas as well as the changes in the composition of these areas across different river reaches, suggesting that the primary drivers of vegetation and land cover change vary across the river system and that different parts of

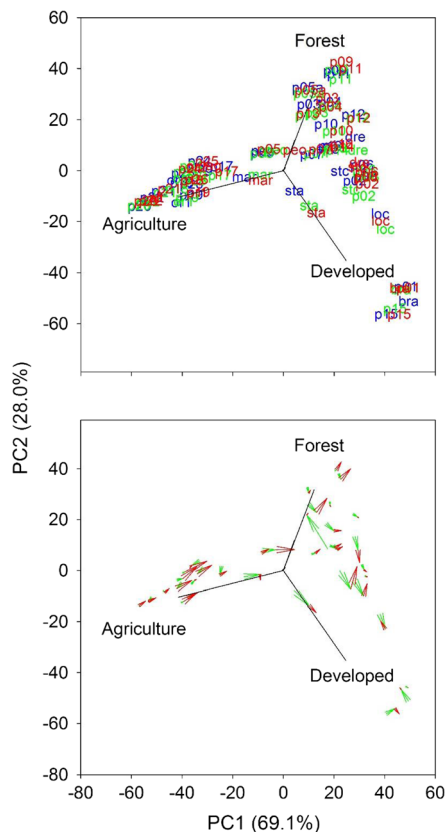


Fig. 6 Principal component analysis (PCA) biplots. The *upper panel* is an ordination using varimax rotation of the percentage of the floodplain within each navigation reach of the Upper Mississippi and Illinois rivers in each floodplain class (*blue symbols* are for 1989, *green symbols* are for 2000, and *red symbols* are for 2010). The *lower panel* is the same ordination as the upper panel but the transition of each reach is shown from 1989 to 2000 (*green*) and from 2000 to 2010 (*red*)

the system offer different collections of habitats and ecosystem functions. Below, we discuss differences in composition and change over time among different areas of this river system and the potential causes and consequences of such differences.

Changes in aquatic areas

Changes in aquatic vegetation are important given the keystone role it plays within parts of the UMRS (Korschgen et al. 1988). Aquatic plants provide food and shelter for macroinvertebrates, fish, and waterfowl (Holland and Huston 1994; Korschgen et al. 1988; Johnson and Jennings 1998; Stafford et al. 2007). The changes in aquatic vegetation in the northern UMR are generally consistent with local observations (De Jager and Yin 2010; Popp et al. 2014). These studies have shown gradual increases in aquatic vegetation since the early 2000s in navigation reaches p04, p08, and p13, along with declines in turbidity and improvements in water clarity. Such increases come following a reported crash in aquatic vegetation in the early 1990s (Rogers 1994; Fischer and Claflin 1995). The 10-year interval of the data we used here would not have captured the timing of such a dramatic decline, and hence, our estimates of aquatic vegetation do not document the very low levels that may have occurred throughout the 1990s. Nevertheless, our results suggest that declines in aquatic vegetation extended well below p13 from 1989 to 2000, with recovery limited to the reaches above p14 from 2000 to 2010.

Aquatic plant growth is potentially influenced by a wide range of factors that span local to regional scales (Moore et al. 2010) including the following: discharge and water levels (Spink and Rogers 1996), light availability and water velocity (Kimber et al. 1995; Best et al. 2001; Kreiling et al. 2007), and nutrient availability (Rogers et al. 1995). Once established, aquatic plants can stabilize sediments and locally improve water clarity, promoting further aquatic plant growth (Madsen et al. 2001). We suggest that the regional nature of the increase in aquatic plant growth in the northern UMR reflects very broad scale improvements in water clarity. Kreiling and Houser (2016) recently documented reductions in suspended solids from tributaries entering the UMR from 1991 to 2014. Improved water clarity may have allowed initial establishment of vegetation patches in places where they had been lost. Once established, these beds likely expanded into deeper water areas as

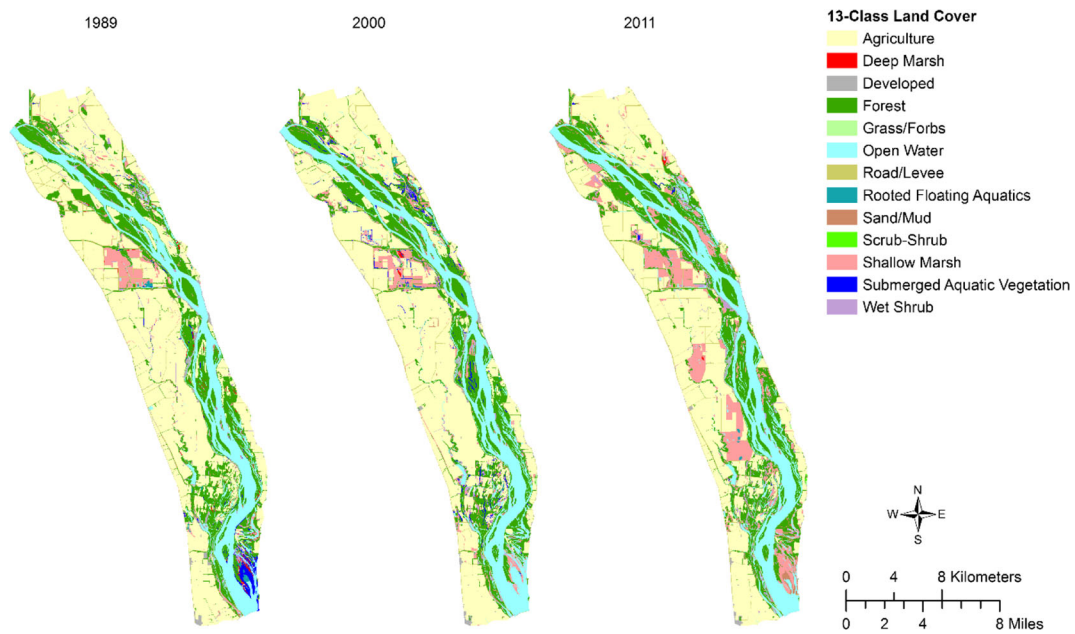


Fig. 7 Navigation reach p21 of the Upper Mississippi River is a good example of the decline in aquatic vegetation from 1989 to 2010, the decline in agricultural area, and the increase in shallow marsh and floodplain forest area from 2000 to 2010

water continued to clear (De Jager and Yin 2010). However, it should be pointed out that local geomorphic conditions are generally favorable for aquatic plant growth in the reaches above p14 (e.g., large shallow impounded areas with slow current velocities), making it possible for improved light conditions to trigger plant establishment and growth.

In contrast to the upper portions of these rivers, both water clarity and geomorphic conditions are generally less favorable for aquatic plant growth in the lower reaches (Yin et al. 2002) and this may explain the lack of recovery below p13 of the UMR and in the lower Illinois River. Additional factors that could prevent aquatic plant growth include the following: sediment resuspension caused by wind, waves and fish (Korschgen 1990; Bellrichard 1994), lack of viability in the seed bank (Kimber et al. 1995; Kenow and Lyon 2009; Sass et al. 2010), and high rates of herbivory (Sass et al. 2009). These factors could interact to limit aquatic plant growth in the lower UMR and Illinois River. However, it might be argued that the lack of aquatic plants in these reaches was somewhat confounded by differences in the data collection methods used in this study. Imagery above p14 was collected at a higher resolution than below p14 in 2010/2011, making it potentially easier to detect aquatic plants above p14. However, the image resolutions should have been more

than sufficient to detect aquatic vegetation in the lower river, if it existed there. It could also be suggested that higher water levels in the lower river during 2011 could have simply made aquatic vegetation less visible. While this is likely to be true, local observations suggest that aquatic plants are generally more abundant in the northern river reaches (Yin et al. 2002; MACTEC Engineering and Consulting 2006; Sass et al. 2010). In addition, recent ad hoc field data collection efforts made by the Upper Mississippi River Conservation Committee in p18 in 2005 and p19 in 2006 found that only 16% of sampled sites contained submerged aquatic plants in these reaches (unpublished data). In contrast, this same group found that 40% of sample sites contained submerged aquatic plants in p03 in 2008 and p06 in 2007 (unpublished data). While this underscores the importance of coupling local field observations with remotely sensed data, a more standardized approach to aerial photo collection might help to better quantify the spatial extent of aquatic vegetation abundance and changes in the UMR in the future.

Changes in floodplain areas

Changes in floodplain land cover were mostly attributable to continued effects of anthropogenic land use. We observed increases in development from 1989 to 2000

throughout the UMR, with weaker increases, and for many reaches, no change in development from 2000 to 2010. Although relatively small, the increases in development within the study area are consistent with previous findings of Hipple et al. (2005). That study showed an approximate increase in population density within the UMR floodplain of 18% from 1990 to 2000 using US census data and that approximately 20–25% of new development in the states that border the UMR took place within the floodplain. Our results suggest that the rate of development within the floodplain may have declined from 2000 to 2010, although some individual navigation reaches continued to show increased development. The relative lack of urban development from 2000 to 2010 may be linked to less favorable economic conditions during the 2000s. In contrast to the ecological impacts of transitions among open water, aquatic vegetation, or floodplain vegetation types, changes in urban development constitute a much more fundamental change in habitat availability and water quality.

Floodplain forests were once the dominant land cover type throughout the UMRS (De Jager et al. 2013). Today, forest cover within the river corridor is highly fragmented due to the effects of impoundment in the northern UMR and agricultural and urban land use in the southern UMR (De Jager and Rohweder 2011). At the start of this study, we anticipated continual reductions in forest cover due to increases in development, agriculture, and cover types associated with the altered hydrological regime of the river system (e.g., herbaceous marsh communities). From 1989 to 2000, there were minor losses of forest cover, but from 2000 to 2010, we noted minor increases in forest cover throughout the UMRS. In the northern portion of the system, the increase in forest cover was associated with a net loss in agricultural land cover and marsh communities. In the southern UMR, the increase in forest cover was also accompanied with increases in marsh communities and declines in agricultural land use (see Fig. 7). The changes from agriculture to forest cover are likely to signify temporally persistent changes, while shifts from agriculture to marsh communities could represent a transient phenomenon, as such would be the case if agricultural producers simply did not plant fields because conditions were too wet. Nevertheless, the shifts away from agricultural land use, although relatively minor, ought to reduce the direct application of nutrients and chemicals to the floodplain and provide habitat for a number of organisms.

Conclusions

The past two centuries have seen significant reductions in both habitat and biotic diversity of large floodplain rivers due to river regulations and watershed land use changes (Schindler et al. 2016). In this respect, the UMRS is similar to large rivers, globally experiencing continued pressures such as alteration of hydrological conditions, invasive species, floodplain development for urban and agricultural areas, pollution, and eutrophication. However, our results indicate that regional improvements in water clarity may have promoted a large-scale increase in aquatic vegetation for some parts of the UMRS during the past decade. Such increases should promote further shifts in the macroinvertebrate, fish, and waterfowl communities that rely on aquatic vegetation for food and shelter. On the floodplain, we observed non-unidirectional changes in anthropogenic land uses (e.g., development and agriculture), suggesting that broader socio-economic conditions may be the primary agents of change on the UMRS floodplain. Nevertheless, recent minor shifts away from agricultural land use and toward floodplain forest and shallow marsh communities could also be accompanied by improvements in a wide range of ecosystem services (e.g., those related to water quality and biodiversity) since such floodplain habitats provide more ecosystem services than agricultural land types (Felipe-Lucia and Comin 2015).

Acknowledgements Funding for this research was provided by the Long Term Resources Monitoring Component of the Upper Mississippi River Restoration Program, a partnership among four Federal agencies (USACE, USEPA, USFWS, USGS) and five state natural resource agencies (Illinois, Iowa, Minnesota, Missouri, Wisconsin). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

References

- Beatty, W. S., Webb, E. B., Kesler, D. C., Naylor, L. W., Raedeke, A. H., Humburg, D. D., Coluccy, J. M., & Soulliere, G. J. (2015). An empirical evaluation of landscape energetic models: mallard and American black duck space use during the non-breeding season. *The Journal of Wildlife Management*, 79, 1141–1151.
- Bellrichard, S.J. (1994). Effects of common carp (*Cyprinus carpio*) on submerged macrophytes and water quality in a backwater lake on the Upper Mississippi River. M.S. thesis submitted to

- the faculty of the graduate school of the University of Wisconsin-La Crosse.
- Best, E. P. H., Buzzelli, C. P., Bartell, S. M., Wetzel, R. L., Boyd, W. B., Doyle, R. D., & Campbell, K. R. (2001). Modeling submersed macrophyte growth in relation to underwater light climate: modeling approaches and application potential. *Hydrobiologia*, *444*, 43–70.
- Cook, T. R., & McClelland, M. A. (2007). *Submersed and rooted floating-leaved aquatic vegetation abundances in the Dresden, Marseilles, and Starved Rock pools, Illinois River, 2005. LTRMP Completion Report 2005Glide42*. La Crosse, WI: U.S. Geological Survey, Upper Midwest Environmental Sciences Center.
- Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T. (1979). *Classification of wetlands and deepwater habitats of the United States* (pp. 131). Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service.
- De Jager, N. R., & Yin, Y. (2010). Temporal changes in spatial patterns of submersed macrophytes in two impounded reaches of the Upper Mississippi River, USA, 1998-2009. *River Systems*, *19*, 129–141.
- De Jager, N. R., Rohweder, J. R., & Nelson, J. C. (2011). Past and predicted future changes in the land cover of the Upper Mississippi River floodplain, USA. *River Research and Applications*. doi:10.1002/tra.1615.
- De Jager, N. R., & Rohweder, J. (2011). Spatial scaling of core and dominant forest cover in the upper Mississippi and Illinois River floodplains, USA. *Landscape Ecology*, *26*, 697–708.
- De Jager, N.R., Rohweder, J.J., Nelson, J.C. (2013). Past and predicted future changes in the land cover of the Upper Mississippi River floodplain, USA. *River Research and Applications*, *29*, 608–618.
- Dieck, J. J., Ruhser, J., Hoy, E., & Robinson, L. R. (2015). General classification handbook for floodplain vegetation in large river systems (ver. 2.0, November 2015), U.S. Geological Survey Techniques and Methods, book 2, chap. A1, p. 51. doi:10.3133/tm2A1.
- Felipe-Lucia, M. R., & Comin, F. A. (2015). Ecosystem services-biodiversity relationships depend on land use type in floodplain agroecosystems. *Land Use Policy*, *46*, 201–210.
- Fink, D., Hochachka, W. M., Zuckerberg, B., Winkler, D. W., Shaby, B., Muson, M. A., Hooker, G., Riedewald, M., Sheldon, D., & Kelling, S. (2010). Spatiotemporal exploratory models for broad-scale survey data. *Ecological Applications*, *20*, 2131–2147.
- Fischer, J. R., & Clafin, T. O. (1995). Declines in aquatic vegetation in navigation pool no. 8 upper Mississippi River between 1975 and 1991. *Regulated Rivers Research and Management*, *11*, 157–166.
- Garvey, J., Ickes, B., & Zigler, S. (2010). Challenges in merging fisheries research and management: the Upper Mississippi River experience. *Hydrobiologia*, *640*, 125–144.
- Guyon, L., Deutsch, C., Lundh, J., & Ulrich, R. (2012). Upper Mississippi River systemic forest stewardship plan. U.S. Army Corps of Engineers. 124 p.
- Hipple, J. D., Dratzkowski, B., & Thorsell, P. M. (2005). Development in the Upper Mississippi Basin: 10 years after the Great Flood of 1993. *Landscape and Urban Planning*, *72*, 313–323.
- Holland, L. E., & Huston, M. L. (1994). Relationship of young-of-the-year northern pike to aquatic vegetation types in backwaters of the Upper Mississippi River. *North American Journal of Fisheries Management*, *4*, 514–522.
- Jakusz, J. W., Dieck, J. J., Langrehr, H. A., Ruhser, J. J., & Lubinski, S. J. (2016). Accuracy assessment/validation methodology and results of 2010–11 land-cover/land-use data for Pools 13, 26, La Grange, and Open River South, Upper Mississippi River System. U.S. Army Corps of Engineers' Upper Mississippi River Restoration Program, Long Term Resource Monitoring Technical Report, 2015–T001, p. 39. <http://pubs.er.usgs.gov/publication/70159276>.
- Johnson, B. L., & Jennings, C. A. (1998). Habitat associations of small fishes around islands in the Upper Mississippi River. *North American Journal of Fisheries Management*, *18*, 327–336.
- Kenow, K. P., & Lyon, J. E. (2009). Composition of the seed bank in drawdown areas of navigation pool 8 of the Upper Mississippi River. *River Research and Applications*, *25*, 194–207.
- Kimber, A., Owens, J. L., & Crumpton, W. G. (1995). Light availability and growth of wild celery (*Vallisneria spiralis*) in Upper Mississippi River backwaters. *Regulated Rivers Research and Management*, *11*, 167–174.
- Kreiling, R. M., Yin, Y., & Gerber, D. T. (2007). Abiotic influences on the biomass of *Vallisneria spiralis* Michx. in the Upper Mississippi River. *River Research and Applications*, *23*, 343–349.
- Kreiling, R. M., & Houser, J. N. (2016). Long term decreases in phosphorus and suspended solids, but not nitrogen, in six Upper Mississippi River tributaries, 1991–2014. *Environmental Monitoring and Assessment*.
- Korschgen, C. E., George, L. S., & Green, W. L. (1988). Feeding ecology of canvasbacks staging on pool 7 of the Upper Mississippi River. In M. W. Weller (Ed.), *Waterfowl in winter* (pp. 237–249). Minneapolis MN: University of Minnesota Press.
- Korschgen, C. E. (1990). *Feasibility study: impacts of turbidity on growth and production of submersed plants*. Report by the U.S. Fish and Wildlife Service, Northern Prairie Wildlife Research Center, La Crosse, Wisconsin: for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, November 1990. EMTc 90–07. 11 pp. (NTIS PB91135475).
- MACTEC Engineering and Consulting, Inc. (2006). Aquatic vegetation survey within the Dresden, Marseilles, and Starved Rock pools of the Upper Illinois waterway. Prepared for the U.S. Army Corps of Engineers Rock Island District. Contract DACW25–00-D-0005. Work Order No. 0024.
- Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W., & Westlake, D.F. (2001). The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, *444*, 71–84.
- Moore, M., Romano, S. P., & Cook, T. (2010). Synthesis of Upper Mississippi River System submersed and emergent aquatic vegetation: past, present, and future. *Hydrobiologia*, *640*, 103–114.
- Naimen, R. J., Decamps, H., & Pollock, M. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, *3*, 209–212.
- Popp, W. A., R. M. Burdis, S. A. DeLain, & M. J. Moore. (2014). Temporal trends in water quality and biota in segments of pool 4 above and below Lake Pepin, Upper Mississippi

- River: indications of a recent ecological shift. Upper Mississippi River Restoration Long Term Resource Monitoring Program Completion Report 2010D6 submitted to the U.S. Army Corps of Engineers, Rock Island, Illinois. 47 pp.
- Rogers, S. J. (1994). Preliminary evaluation of submersed macrophyte changes in the Upper Mississippi River. *Lake and Reservoir Management*, 10, 35–38.
- Rogers, S. J., McFarland, D. G., & Barko, J. W. (1995). Evaluation of the growth of *Vallisneria americana Michx.* in relation to sediment nutrient availability. *Lake and Reservoir Management*, 11, 57–66.
- Sass, G. G., McClelland, M. A., Cook, T. R., Irons, K. S., O'Hara, T. M., & Michaels, N. N. (2009). *Factors supporting or limiting submersed aquatic vegetation establishment and growth in the Starved Rock reach of the Illinois River*. Rock Island District: U.S. Army Corps of Engineers Technical Report.
- Sass, G.G., Cook, T.R., Irons, K.S., McClelland, M.A., Michaels, N.N., & O'Hara, T.M. (2010) *Experimental and comparative approaches to determine factors supporting or limiting submersed and aquatic vegetation in the Illinois River and its backwaters*. LTRMP Report, U.S. Geological Survey, La Crosse, WI: Upper Midwest Environmental Sciences Center.
- Schindler, S., et al. (2014). Multifunctionality of floodplain landscapes: relating management options to ecosystem services. *Landscape Ecology*, 29, 229–244.
- Schindler, S., et al. (2016). Multifunctional floodplain management and biodiversity effects: a knowledge synthesis for six European countries. *Biodiversity and Conservation*, 25, 1349–1382.
- Spink, A., & Rogers, S. (1996). The effects of a record flood on the aquatic vegetation of the Upper Mississippi River System: some preliminary findings. *Hydrobiologia*, 340, 51–57.
- Stafford, J. D., Horath, M. M., Yetter, A. P., Hine, C. S., & Havera, S. P. (2007). Wetland use by mallards during spring and fall in the Illinois and central Mississippi River valleys. *Waterbirds*, 30, 394–340.
- Strauss, E. A., Richardson, W. B., Cavanaugh, J. C., & Bartsch, L. A. (2011). Effect of habitat type on in-stream nitrogen loss in the Mississippi River. *River Systems*, 19, 261–269.
- Theiling, C.H., Korschgen, C., De Haan, H., Fox, T., Rohweder, J., & Robinson, L. (2000). Habitat needs assessment for the Upper Mississippi River System: technical report. U.S. Geological Survey, Upper Midwest Environmental Sciences Center: La Crosse, WI, contract report prepared for U.S. Army Corps of Engineers, St. Louis District, St. Louis, MO.
- Tomaselli, V., et al. (2013). Translating land cover/land use classifications to habitat taxonomies for landscape monitoring: a Mediterranean assessment. *Landscape Ecology*, 28, 905–930.
- Venterink, H. O., Vermaat, J. J. E., Olde Venterink, H., Vermaat, J. J. E., Pronk, M., Wiegman, F., & Verhoeven, J. T. A. (2006). Importance of sediment deposition and denitrification for nutrient retention in floodplain wetlands. *Applied Vegetation Science*, 9, 163–174.
- WEST Consultants, Inc. (2000). Final report: Upper Mississippi River and Illinois waterway cumulative effects study, volume 1: geomorphic assessment. *ENV Report 40–1*.
- Yin, Y., Boma, P., & Sauer, J. (2002). *Aquatic vegetation survey for the Upper Mississippi and Illinois Waterway Navigation Study: pool 14–19. Report to the Rock Island District*. Rock Island, IL: U.S. Army Corps of Engineers.