

## CONSEQUENCES OF HUMAN-ALTERED FLOODS: LEVEES, FLOODS, AND FLOODPLAIN FORESTS ALONG THE WISCONSIN RIVER

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**Abstract.** Flood-control levees are generally thought to increase flood height and velocity for a given discharge. While extensive areas of floodplain in the United States are leveed, the ecological impacts of levees have largely been ignored relative to other anthropogenic impacts to large river floodplains. We examined a century of flood control along the Wisconsin River by comparing simulated flood regimes under “levee” and “levee-removal” scenarios. We also used field sampling to determine if levees had altered the distribution of dominant floodplain forest trees. Increases in flood stage (height) due to levees were minor, only a few centimeters. This was primarily due to the location of the levees, set back hundreds of meters into the floodplain in some areas. Increases in overbank flood velocities due to levees were minimal compared to increases caused by channel constriction and by increased flood magnitude. Generally, levees had a greater impact on stage and overbank flood velocities of larger magnitude events. The mean number of floods and number of days flooded were lower in areas outside (on upland sides) of levees, and stream power was zero in these areas due to a lack of any inundation. These areas also had lower importance values (IV) for several flood-tolerant tree species (*Acer saccharinum* and *Fraxinus pennsylvanica*) and higher IVs for some flood-intolerant species (*Quercus velutina* and *Q. ellipsoidalis*). Furthermore, areas inside levees (between the levee and the channel) were no different from completely unleveed areas in the number of floods, number of days flooded and in IVs of several dominant tree species. The levee location (set back into the floodplain) resulted in a similar historic flood regime, and thus, similar abundances of floodplain tree species in areas inside levees as compared to completely unleveed areas. Setback levees can provide an important compromise by maintaining the relative abundance of tree species normally found in unleveed areas, while also allowing some flood control. Floodplain restoration involving levee removal should generally target the removal of mainline levees (those adjacent to the channel) rather than removal of setback levees.

**Key words:** flood-control levees; floodplain vegetation; flood power; reconstructed flood regime; Upper Mississippi Valley; Wisconsin River; velocity.

### INTRODUCTION

Nearly all major rivers in the Northern Hemisphere have been altered for navigation, agriculture, power generation, or flood control (Dynesius and Nilsson 1994, Power et al. 1995b, Vitousek et al. 1997). In the U.S., flow regulation occurs on nearly 98% of rivers (Vitousek et al. 1997). While nation-wide estimates of leveed rivers are problematic, it has been estimated that there are at least 40 000 km of levees, floodwalls, embankments, and dikes in the United States (Johnston Associates 1989). There are ~17 000 km of levees in the Upper Mississippi Valley (Tobin 1995) and over 3218 km of mainline levees along the Lower Mississippi (Nunnally et al. 1987). These ubiquitous hydrologic alterations have a profound impact on riparian ecosystems (Chapin et al. 1997, Vitousek et al. 1997), primarily through the disruption of flood pulses (Junk

et al. 1989). Flood pulses are critical in the dynamics of seed dispersal, plant establishment, nutrient cycling, scouring, sediment deposition, and maintenance of species richness (Johnson et al. 1976, Skoglund 1990, Stromberg et al. 1993, Bendix 1994, Nilsson et al. 1997, Friedman and Auble 1999, Perez et al. 1999).

Floods also govern much of the spatial pattern in floodplains (Bayley 1995, Miller et al. 1995) and, as such, the heterogeneity of large river floodplains is maintained by the flood regime (Ward and Stanford 1995). Furthermore, a given flood can vary tremendously in terms of flow, power, and resulting sediment deposition patterns (Magilligan 1992, Woltemade 1994, Lecce 1997a, b, Knighton 1999) with variation in flooding occurring both longitudinally (along the drainage network) and laterally (with position and elevation in the floodplain; Sparks and Spink 1998). The effects of flooding on vegetation also tend to be patchy because vegetation patterns are influenced by the annual water regime as well as large catastrophic floods (Sparks and Spink 1998). Determining how modifications of disturbance regimes alter natural levels of variability and spatial heterogeneity remains a challenge

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in floodplains, as does evaluating the relative importance of small vs. large flood events.

Although flood-control levees have significantly altered flood regimes throughout the U.S., the long-term effects of levees on floodplain vegetation are largely unknown. When examining the response of floodplain vegetation to hydrologic alterations, few studies consider changes more than a decade after a hydrologic alteration (Smith et al. 1991, Nilsson et al. 1997; but see Rood et al. 1995, Nelson and Sparks 1998) even though the legacy of floods and nonflood periods may dominate forest age structure and species composition for decades (Sparks and Spink 1998). In addition, focus has been primarily on the effects of dams on floodplain vegetation (Reily and Johnson 1982, Williams and Wolman 1984, Rood and Mahoney 1990, Pautou et al. 1991, Gup 1994, Ligon et al. 1995, Rood et al. 1995, Nilsson et al. 1997, Friedman et al. 1998, Johnson 1998). Very few studies directly examine the ecological effects of flood-control levees (Smith et al. 1998, Yin 1998).

We examine a leveed reach of the Wisconsin River near Wisconsin Dells, Wisconsin, USA. Over a century of flood control via levees has had the potential to alter both the historical pattern of floods and the composition of floodplain forests. The area is also under consideration for levee removal, and as such, we discuss the implications of our results for the management and restoration of large-floodplain river systems dominated by flood-control levees. We address two major questions.

#### *How have flood-control levees influenced the flood regime of the Wisconsin River?*

In addition to restricting overbank flooding, levees have been shown to increase flood stage (height) and flow velocity for a given discharge (Kazmann 1972, Belt 1975, Pitlick 1997). The levee system along the Wisconsin River constrains overbank flooding on both banks of the river, but is set back hundreds of meters from the main channel in some places (in contrast to mainline levees that are adjacent to the channel). We simulated the flood regime under both "levee" and "levee-removal" scenarios on a leveed 4-km subset of the reach to quantify changes in the area inundated, flood stage, and overbank flow velocity. Secondly, we examined an entire 15-km reach that included completely unleveed areas. Over this larger area, we reconstructed the flood regime on 100 sampling plots distributed among three locations relative to levees: inside levees (between the levee and the channel),  $n = 34$ ; outside levees (upland side of levees),  $n = 33$ ; and completely unleveed areas,  $n = 33$ . Our primary goal was to determine the importance of levees relative to other factors (e.g., floodplain and channel morphology) in influencing the variability of floods.

#### *Have flood-control levees influenced the distribution of floodplain tree species?*

Floodplain species are often distributed along gradients of flood frequency, duration, and physical force (Bedinger 1979, Yin 1998). We compared the relative abundance of floodplain species on the plots in the three locations described above: inside levees, outside levees, and unleveed areas. We also related the forest composition of the plots to flood regime variables obtained from levee and levee-removal simulation scenarios. Our specific goals were to (1) determine if levees have had an effect on the relative abundance and spatial distribution of flood-tolerant and flood-intolerant species and (2) determine which aspects of the flood regime (frequency, duration, or flood power) best explained the differences in vegetation.

## METHODS

### *Study site*

The floodplain along the Wisconsin River between Wisconsin Dells and Portage, Wisconsin (Fig. 1) is covered by alluvial deposits of Pleistocene, Holocene, and Historical ages (Clayton and Attig 1989), as well as 12 000-yr-old glacial lake deposits (Liegel 1982), consisting primarily of silt loams, clay loams, sand loams, and sand (Liegel 1988, Lange 1990). Gentle ridge and swale topography (Liegel 1988) has created a mosaic of habitat ranging from marsh and meadows to floodplain forest, prairie, and oak savannah, as the area lies south of the tension zone separating the Northern Hardwoods floristic province from the Prairie-Forest province (Curtis 1959). Past draining of wetlands, grazing, harvesting of hay, and agricultural conversion have altered much of the landscape. The area is of historical significance as it provided the inspiration and setting for *A Sand County Almanac* (Leopold 1949). Currently, part of the area is managed by the Sand County Foundation as a working example of Leopold's "land ethic."

Because the Wisconsin River is a large-floodplain river with low relief, overbank flooding has the potential to inundate a large area extending several kilometers from the main channel. However, two major levees, the Caledonia and Lewiston, restrict overbank flooding on both sides of the river. Scattered portions of the floodplain have been leveed since the 1860s and the contemporary levee configuration was completed at the turn of the twentieth century. Perpendicular levees and natural topographic relief prevent backfilling behind the levees during floods, although some seepage does occur. Levee failure during the flood of 1938 allowed some historic inundation of the floodplain.

Flow is regulated by 24 upstream dams, including a hydroelectric dam immediately upstream that causes daily fluctuations in flow. Annual rainfall in the area averages 81 cm and spring and fall flows average 360 m<sup>3</sup>/s (12 900 cfs [cubic feet per second]) and 120 m<sup>3</sup>/s

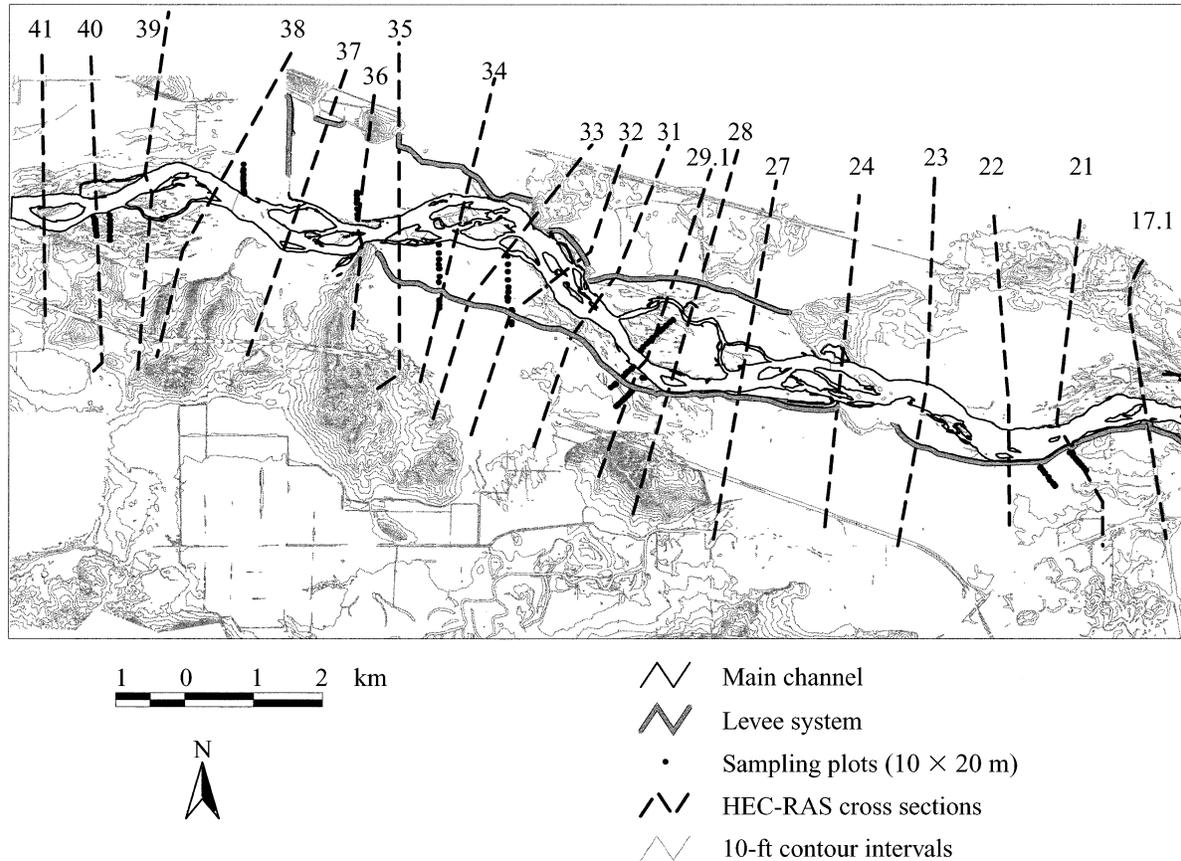


FIG. 1. The Wisconsin River between the towns of Wisconsin Dells (west) and Portage (east). Cross-sectional comparisons were made only among cross sections 29.1–35. Comparison at the plot level utilized plots located throughout a broader extent of the floodplain from cross sections 21–38. Contour lines represent 10-foot (~3.05-m) intervals.

(4400 cfs), respectively. The flood threshold according to the National Weather Service (in terms of flood warnings) is approximately 1320 m<sup>3</sup>/s (46 800 cfs; data available online).<sup>2</sup> However, flows of ~560 m<sup>3</sup>/s (less than the 2-yr event; Table 1) are capable of inundating the most low-lying portions of the floodplain and back-water sloughs. We established 100 plots in areas inside levees, outside levees, and in completely unveeved areas to compare flood regime and vegetation changes across the floodplain using both simulation modeling and field sampling.

*Flood simulation.*—HEC-RAS software (Hydrologic Engineering Center, River Analysis System, U.S. Army Corps of Engineers 1998) was used to quantify aspects of the flood regime in both levee and levee-removal scenarios. HEC-RAS is a standard modeling software package for estimating flood stage, extent, and flood power. HEC-RAS performs a steady-flow analysis using a series of cross sections (Figs. 1 and 2b) representing topography and hydraulic roughness (Manning’s *n*) for homogenous sections of a reach. Water

surface profiles are calculated using the standard step method, which sequentially solves a one-dimensional energy equation between cross sections (Hoggan 1997). Estimates of Manning’s *n* and stage–discharge relationships for the study reach were obtained courtesy of

TABLE 1. Flood probability estimates for the Wisconsin River at Wisconsin Dells, Wisconsin, under current regulated (dammed) conditions.

Discharge (m <sup>3</sup> /s)	Discharge (cfs) <sup>†</sup>	Recurrence interval (yr)	Probability of occurrence in a year
950	33 000	2	0.50
1350	48 000	5	0.20
1590	56 000	10	0.10
1860	66 000	25	0.04
2050	72 000	50	0.02
2220	79 000	100	0.01
2390	84 000	200	0.005
2590	91 000	500	0.002

Note: Based on simulated data from Krug and House (1980).

<sup>†</sup> Discharge is reported in cubic feet per second (cfs); 1 cubic foot ≈ 0.0283 m<sup>3</sup>.

<sup>2</sup> URL: <http://waterdata.usgs.gov/nwis-w/WI/?statnum=05404000>

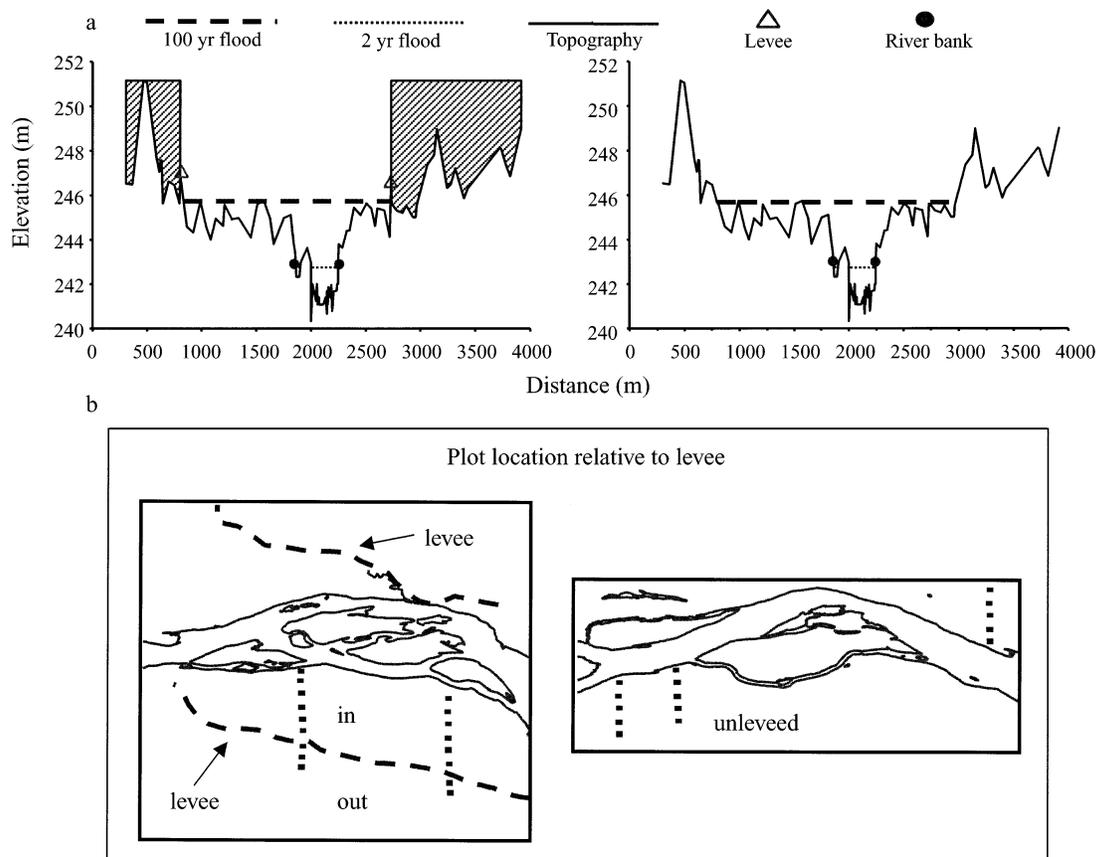


FIG. 2. Flood regime comparisons. Cross-sectional views of the floodplain, showing an example of a cross section used for HEC-RAS analysis. The left panel depicts the actual levee configuration, and the right panel depicts the levee-removal scenario. The flood regime was simulated for all vegetation sampling plots under the "levee" configuration and under the scenario of "levee removal." The hatched area indicates areas restricted from flooding due to levees. (b) Aerial view of the location of plots (shown as dark squares) relative to the levee system (shown as hatched lines).

the Wisconsin Department of Natural Resources (A. R. Luloff, *personal communication*).

Flood probabilities at Wisconsin Dells (Table 1) were calculated using simulated flows to account for non-stationarity in the actual discharge time series due to the influence of upstream dams (i.e., different dams were constructed and operated throughout various intervals of the actual discharge time series; Krug and House 1980). Krug and House (1980) simulated regulated and unregulated annual maximum instantaneous discharges from 1915 to 1976. The simulated regulated data represent flows that would have occurred if the dam at the Wisconsin Dells were in continuous operation for the entire time series. Flows were fit to a log Pearson III distribution (Interagency Advisory Committee on Water Data 1982) using PeakFQ software (USGS 1998) and are similar but not identical to other published flood probabilities for the Wisconsin River (Krug and House 1980).

The influence of levees on the flood regime was determined several ways. On a 4-km subset of our reach (cross sections 29.1–35, Fig. 1) we examined changes

in the areal extent of flooding by comparing levee and levee-removal simulations. The levee scenario simulates the flood regime given the contemporary configuration of levees; while the levee-removal scenario simulates flood patterns after the removal of the levees from cross sections 29.1–35. Using these same cross-sections, we examined changes in flood stage and overbank velocity by comparing the results of levee and levee-removal simulations among cross sections. Levee-removal simulations were not possible at other locations due to the lack of topographic data on the upland side of levees at several cross sections.

The impact of levees was also examined using plot-level data from 100 plots, sampling a greater extent of the floodplain (from cross sections 21–38) that included completely unleveed areas (Fig. 1). The number of floods, days of flooding, shear stress, and unit stream power were compared among three locations across the floodplain: areas inside levees, outside levees, and in completely unleveed areas (Fig. 2a). The historic flood regime of each sampling plot (Table 2) was reconstructed by using the stage–discharge relationship from

TABLE 2. Range of values for the reconstructed flood regime (1935–1996) calculated using HEC-RAS software (see Fig. 2b).

Flood regime variable and definition	Levee median (range)	Levee-removal median (range)
Flood events		
Total no. flood events on plot	7 (0–210)	16 (0–267)
GS flood events		
Total no. flood events on plot during growing season	4 (0–95)	8 (0–125)
Days flooded		
Total no. days of inundation of plot	21 (0–1139)	48 (0–1669)
GS days flooded		
Total no. days of inundation of plot during growing season	12 (0–461)	25 (0–719)
Shear stress		
Overbank-flow shear stress of the 100-yr flood event (N/m <sup>2</sup> ) <sup>†</sup>	0.95 (0–7.03)	1.55 (0–6.78)
Unit stream power		
The overbank power of the 100-yr flood event (W/m <sup>2</sup> ) <sup>‡</sup>	0.22 (0–1.80)	0.32 (0–1.75)

Note: The flood regime was reconstructed for 100 sampling plots under a levee scenario (given the contemporary configuration of levees) and under the levee-removal simulation.

<sup>†</sup> Newtons per square meter.

<sup>‡</sup> Watts per square meter.

the nearest HEC-RAS cross section (Fig. 1). Each plot's inundating discharge was the flood stage equal to the mean elevation of that plot. The total number of flood events and days inundated were determined by comparing a plot's inundating discharge with the gauged record of discharges from 1935 to 1996.<sup>2</sup> Historical temperature data from the Midwestern Regional Climate Center (in Champaign, Illinois, USA) were used to determine the first and last day of frost at Portage, Wisconsin, to calculate the total number of flood events, and days inundated during the growing season.

Stream power influences sediment transport, channel shape, and channel migration and is commonly measured as shear stress or unit stream power. Shear stress and unit stream power of the 100-yr event were calculated for each individual sampling plot. Shear stress represents the force per unit area exerted on a streambed by flowing water (Ligon et al. 1995). Shear stress (N/m<sup>2</sup>) was calculated for each plot using the following equation (Friedman and Auble 1999):

$$\tau = \rho \times g \times D \times S$$

where  $\rho$  = density of water (1000 kg/m<sup>3</sup>),  $g$  = the acceleration due to gravity (9.807 m/s<sup>2</sup>),  $D$  = the depth of flow (m), and  $S$  = the dimensionless energy grade line.  $D$  and  $S$  were determined using HEC-RAS. Total stream power measures power per unit length, but is often expressed relative to stream width as unit stream power, or the power per unit wetted area of specific reach (Magilligan 1992). Unit stream power (W/m<sup>2</sup>) was calculated as follows (Bendix 1994, Baker and Costa 1987):

$$\omega = \gamma \times D \times S \times v$$

where  $\gamma$  = the specific weight of water (9800 N/m<sup>3</sup>) and  $v$  = flow velocity (m/s) and  $D$  and  $S$  are as defined above.

For these same plots, the historical flood regime of each plot under the levee-removal scenario was also determined and compared to the levee scenario.

*Vegetation transects.*—Ten stratified random transects (0.5–1.5 km in length) were established perpendicular to the channel in floodplain forest in undisturbed areas (i.e., no evidence of recent logging or agriculture and more than 25 m from roads). Eight to ten 10 × 20 m plots were established at random intervals (at least 40 m apart) along each transect. A total of 100 plots were distributed among areas inside levees ( $n = 34$ ), areas outside (behind) levees ( $n = 33$ ), and completely unleveed portions of the floodplain ( $n = 33$ ; Fig. 2a)—the same plots examined for flood regime changes. On each plot, all trees greater than 2.5 cm dbh (diameter at breast height) were measured and identified to species. Relative abundance and relative basal area were summed to calculate a modified importance value (IV), ranging from 0 to 2, for each species on each plot:

$$IV = \frac{(\text{number of individuals of one species on a plot}) / (\text{total number of individuals on plot}) + ((\text{basal area of a species}) / (\text{total basal area of all species on the plot}))}{2}$$

The importance values provide a useful combined measure of abundance while taking into account the basal area of the individuals on a plot. The distance of each plot from the river was determined in the field using a global positioning system (GPS) with <1 m horizontal accuracy. The mean elevation of each plot

was measured from an elevation grid interpolated from a digital terrain model with two-foot (0.6096-m) accuracy using a geographic information system. This was primarily because the vertical GPS measurements were less accurate than the horizontal measurements.

#### Statistical analyses

**Flood regime.**—The area inundated was compared between the levee and levee-removal scenarios, as were changes in stage and velocity. We used analysis of covariance (ANCOVA, SAS 1989) to compare the levee flood regime on plots among the three locations: inside levees, outside levees, and unleveed areas (Fig. 2a), after accounting for distance from the river and the relative elevation of the plot. When significant effects ( $P \leq 0.05$ ) of levees were found in the ANCOVA, Tukey's Honestly Significant Difference (HSD) test was used to compare means.

Comparison of these three areas was important for several reasons. An assumption of the levee-removal simulation is that a century of geomorphic change has been consistent laterally along each cross section. Realistically, areas inside the levees have likely diverged geomorphically from areas outside the levees. For this reason, actual unleveed portions of the floodplain represent the variability of unleveed areas better than cross sections where levee removal has only been simulated. The comparison of the flood regime in these three locations also links the flood regime changes to the vegetation data that were collected at the same three locations.

**Vegetation.**—We determined if levees had an effect on floodplain forest patterns using two methods. First, abundance, basal area, and importance values (IV) of species were compared among three locations relative to levees: areas inside levees, outside levees, and in completely unleveed areas (Fig. 2a). We examined only the most common species: *Acer saccharinum* (silver maple), *Betula nigra* (river birch), *Fraxinus pennsylvanica* (green ash), *Quercus bicolor* (swamp white oak), *Q. velutina* (black oak), and *Q. ellipsoidalis* (northern pin or Hill's oak). Because *Q. velutina* and *Q. ellipsoidalis* commonly hybridize and are extremely difficult to distinguish in the field, they were grouped in all analyses. ANCOVA was used to detect differences due to levee location after accounting for the effects of plot elevation (relative to the 2-yr flood stage) and distance to the river, both of which could influence the distribution of floodplain trees. Due to the extreme non-normality of species' densities, basal area and importance values (which could not be normalized through transformations), ANCOVA was performed on the ranks of the response variables. When significant effects ( $P \leq 0.05$ ) of levees were found in the ANCOVA, Tukey's HSD test was used to compare the means.

Species that were affected by levee location were grouped into a set of either flood-intolerant (*Q. velutina*

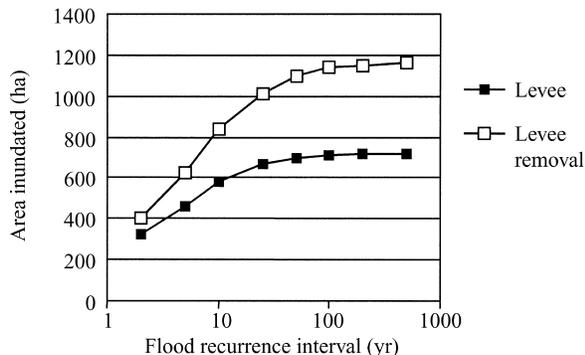


FIG. 3. Extent of flooding. Difference in the area inundated between the levee and levee-removal simulations for the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr floods.

Note: flood recurrence intervals are plotted on a log scale.

and *ellipsoidalis*) or flood-tolerant species (*A. saccharinum* and *F. pennsylvanica*; Teskey and Hinckley 1977). We then related the species grouping to plot-level flood regime variables from the levee and levee-removal simulations. The levee-removal scenario was used to approximate the relative flood regime of plots before the levees were installed. This was to determine whether modern vegetation patterns reflect the contemporary levee flood regime or whether current tree distribution patterns are relicts of the previous flood regime before the levees were in place. Spearman rank correlation coefficients were calculated between the IVs and the simulated flood regime variables.

We also determined which aspects of the levee flood regime (frequency, duration, shear, power) explained more of the variance in vegetation patterns. Principal components analysis (PCA) was used to summarize the flood regime variables obtained from the levee simulations. Then, the abundance, basal area, and IVs of the species flood tolerance groups were related to the PCA axes, distance and elevation using forward stepwise multiple regression. Logistic regression was also conducted with the same independent variables, but using species presence as the dependent variable.

Lastly, we determined whether larger, mature individuals (potentially established before levee construction) and smaller (younger) individuals showed differential responses to the levees. All of the above analyses were repeated after separating individual trees in two size-classes: saplings (2.5–5 cm dbh) and adults ( $\geq 25$  cm dbh), representing two very approximate, yet distinct, age classes. The minimum size of adults (25 cm dbh) was necessary (in part) because a larger basal area cutoff resulted in very few individuals in the adult category.

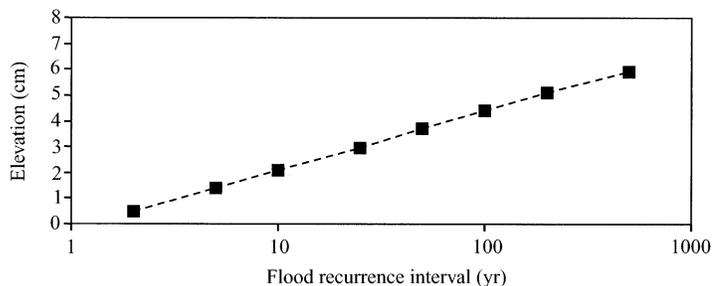
## RESULTS

### *How have flood-control levees influenced the flood regime of the Wisconsin River?*

At the level of the entire floodplain, the area inundated increased greatly with levee removal (Fig. 3).

FIG. 4. Mean difference in water-surface elevation between levee and levee-removal simulations (from cross sections 29.1–35) for the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr floods.

Note: flood recurrence intervals are plotted on a log scale.



The 2-yr flood inundated 320 ha while leveed and 400 ha with simulated levee removal. Greater differences were evident for the larger magnitude flood events, as the 500-yr flood event inundated an area of 720 ha and 1160 ha, under the levee and levee-removal scenarios, respectively.

On a cross-sectional basis, flood heights increased only slightly due to levees, on the order of centimeters (Fig. 4). The mean difference in flood stage among cross-sections between the levee and levee-removal scenarios ranged from 0.49 cm for the 2-yr flood event, to 4.39 cm for the 100-yr event, and 5.90 cm for the 500-yr event. The overbank velocity of flood-

waters varied from 0.06 to 0.20 m/s for the 2-yr event, with small increases due to levees (0.0114 m/s at most; Fig. 5) for most cross sections. Cross sections 29.1 and 33 are exceptions, where the influence of floodplain morphology is likely the cause. At cross section 29.1 there was no right overbank inundation for the 2-yr event with levees, while a low-lying backwater area (deeper than and disconnected from the main channel flows) was inundated upon levee removal, leading to an increase in overbank flow velocity due to the depth of this backwater area. At cross section 33 for levee removal, a low-lying backwater area (that is also disconnected from the main channel) is much shallower than the overbank flows connected to the channel, leading to slower flows after levee removal. In general, greater differences in overbank velocity between levee and levee-removal scenarios were evident for larger magnitude events. However, even for the 100-yr-flood event, increases of only 0.02–0.03 m/s occurred at cross sections.

At the plot level, the flood regime varied based on whether a plot was located inside levees, outside, or in unleveed areas (Fig. 6). The mean number of floods, floods during the growing season, days inundated, and days inundated during the growing season were all significantly lower (zero) in areas outside of levees. However, these same flood regime measures were not significantly different between plots inside levees and plots in completely unleveed areas (Fig. 6).

In the case of flood power (both shear stress and unit stream power), the flood power of the 100-yr event was zero—nonexistent outside of levees due to lack of any flows (i.e., the levees are not overtopped by the 100-yr event; Fig. 6). Power inside the levees was lower than in completely unleveed areas.

*Have flood-control levees influenced the distribution of floodplain tree species?*

After accounting for distance and elevation, several species responded to the plot location relative to levees. *Q. velutina* and *ellipsoidalis* had higher IVs outside levees (Fig. 7). *A. saccharinum* and *F. pennsylvanica* had lower IVs outside levees. IVs for the flood-tolerant *A. saccharinum* and *F. pennsylvanica* were indistinguishable between areas inside levees and unleveed areas. There were no differences in the IV for *B. nigra*

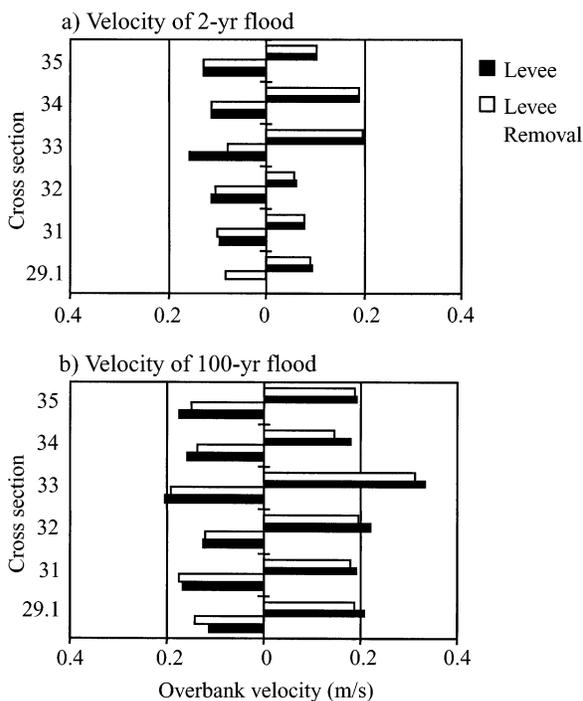


FIG. 5. Changes in overbank water velocity due to levees at individual river cross sections from upstream cross section 35 to downstream cross section 29.1. Both the right and left overbank velocities are shown; values to the right of 0 represent left overbank velocities; values to the left of 0 represent right overbank flood velocities (when facing downstream from cross section 35). (a) Left and right overbank flow velocities for the 2-yr flood event. (b) Left and right overbank flow velocities for the 100-yr flood event.

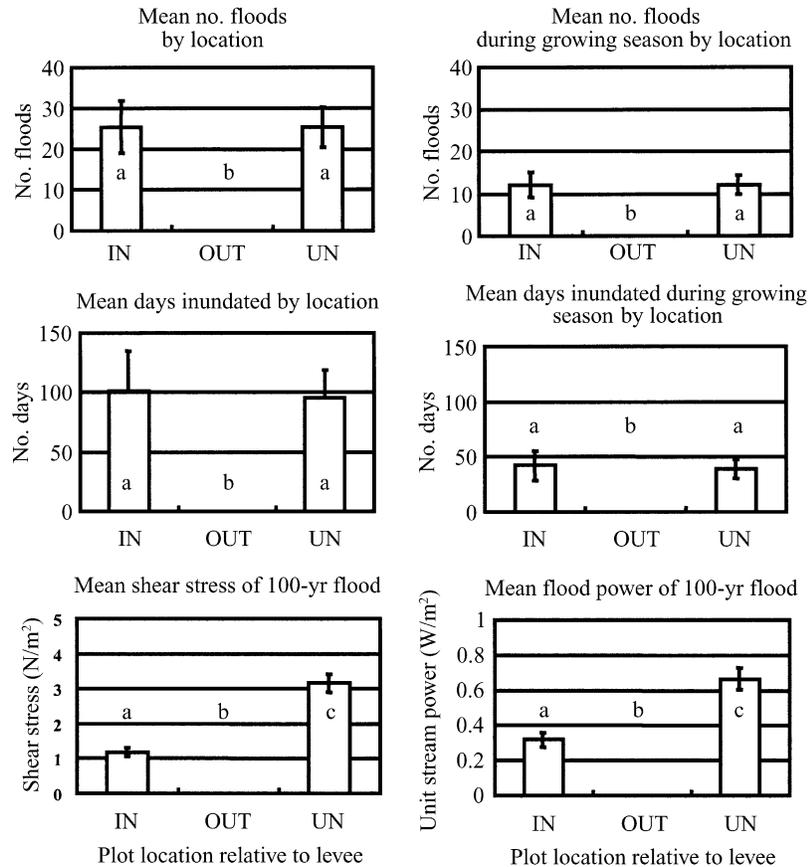


FIG. 6. Changes in flood regime due to levees according to plot location. Letters indicate significant differences in ANCOVA accounting for distance from the river and elevation of plots relative to the height of the 2-yr flood. Error bars show  $\pm 1$  SE. Plot location abbreviations are: IN, inside levees ( $n = 34$ ); OUT, outside levees ( $n = 33$ ); UN, unveeved areas ( $n = 33$ ).

and *Q. bicolor* among the levee treatments (Fig. 7). Significance levels for density and basal area were qualitatively similar to those for IV and are not shown.

The flood regime under the levee scenario explained more of the variance in vegetation patterns on plots than the levee-removal flood regime (Table 3), indicating that the current vegetation patterns are not relicts of the flood regime from before the levees were installed, but do reflect the contemporary levee configuration. The IVs of flood-tolerant species were positively correlated with the number of floods ( $r = 0.44$ ), number of floods during the growing season ( $r = 0.44$ ), days flooded ( $r = 0.39$ ), days flooded during the growing season ( $r = 0.39$ ), and shear stress ( $r = 0.45$ ), and unit stream power ( $r = 0.42$ ). The IVs of flood-intolerant species were negatively correlated with the same variables ( $r$  ranging from insignificant to  $-0.39$ ; Table 3).

The flood regime resulting from the contemporary levee configuration was summarized by two PCA axes that explained 98% of the variance in the flood variables (Table 4a). Axis 1 summarized all the variables:

flood frequency, duration and power, while Axis 2 distinguished the physical force variables (shear stress and unit stream power of the 100-yr flood) from the flood duration measures (Table 4b).

Flood frequency and duration (number of floods, days flooded, and physical force) generally explained more of the variance in vegetation patterns than did distinguishing flood power from the duration variables (Table 5). The PCA scores for axes 1 and 2 along with distance or elevation of the plots explained up to 48% of the variance in flood-intolerant species (Table 5). Axis 1, axis 2, distance, and elevation were significant in predicting the presence of flood-intolerant species with a pseudo  $r^2 = 0.50$  (Table 6). For flood-tolerant species, axis 1 and distance explained 34% of the variance in the IVs (Table 5). In logistic regression, distance explained the presence of flood-tolerant species, with a pseudo  $r^2 = 0.36$  (Table 6).

Large (adult) and small (sapling) size classes generally responded similarly to the levee treatments, except in the case of flood-tolerant saplings (Fig. 8). The importance values of both large and small size-classes

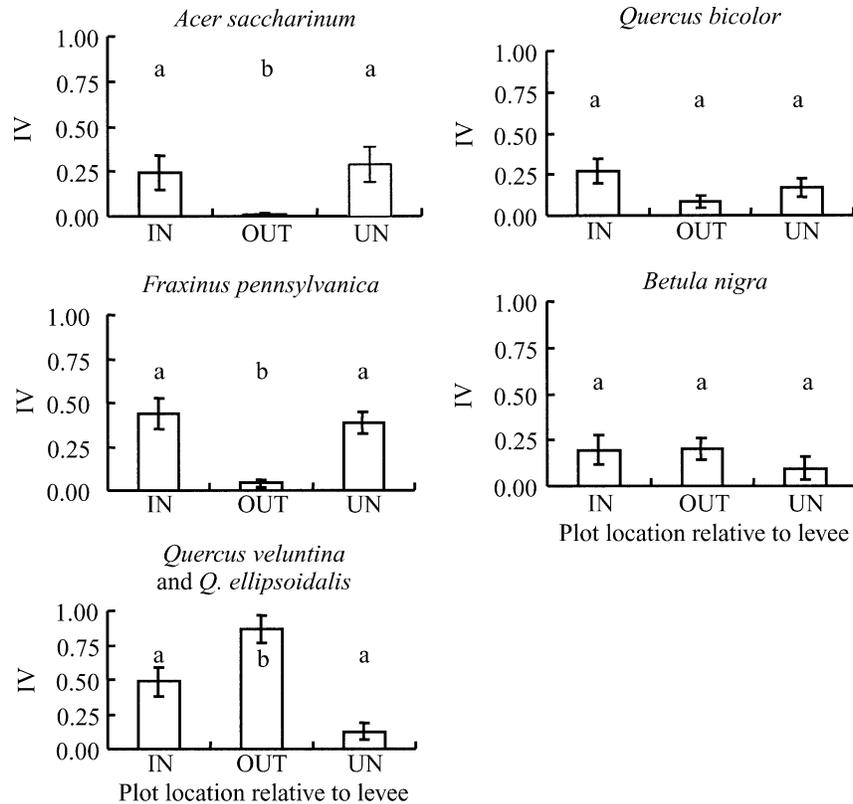


FIG. 7. Influence of levees on the importance values of different species. Areas outside levees were significantly different only for *A. saccharinum*, *F. pennsylvanica*, *Q. velutina*, and *Q. ellipsoidalis*. Letters indicate significant differences in the ranks of the IVs in ANCOVA accounting for distance from the river and elevation of plots relative to the height of the 2-yr flood. Error bars show  $\pm 1$  SE. Plot location abbreviations are: IN, inside levees ( $n = 34$ ); OUT, outside levees ( $n = 33$ ); UN, unleveed areas ( $n = 33$ ).

of flood-intolerant *Q. velutina* and *Q. ellipsoidalis* increased outside levees. IVs of the adult size class of *F. pennsylvanica* decreased outside of levees, but there were no differences in IVs of flood-tolerant saplings among levee treatments inside, outside or in unleveed areas.

PCA Axis 1 almost always explained more vari-

ability in the large size-classes than the other variables (Tables 5 and 6). The relative elevation of the plot and Axis 1 explained more of the variability in the distribution of flood-intolerant saplings than other variables (Table 5). None of the flood regime variables explained much of the variability in the flood-tolerant saplings of *F. pennsylvanica* (Tables 5 and 6).

TABLE 3. Spearman correlation coefficients between ranks of summed importance values for flood-intolerant (*Q. velutina* and *Q. ellipsoidalis*) and flood-tolerant (*A. saccharinum* and *F. pennsylvanica*) species vs. aspects of the flood regime.

Flood regime variable	Flood intolerant		Flood tolerant	
	Levee	Levee removal	Levee	Levee removal
Flood events	-0.32*	NS	0.44†	NS
Growing season flood events	-0.33*	NS	0.44†	NS
Days flooded	-0.27*	NS	0.39†	NS
Growing season days flooded	-0.28*	NS	0.39†	NS
Shear stress (N/m <sup>2</sup> )	-0.54†	-0.39***	0.45†	0.34*
Unit stream power (W/m <sup>2</sup> )	-0.47†	-0.39***	0.42†	0.38†

Note: The flood regime was reconstructed for each vegetation sampling plot under the levee scenario (the contemporary configuration of levees) and under the levee-removal scenario (representing relative flooding before the levees were installed). Flood regime variables are described in Table 2.

\*  $P < 0.05$ ; \*\*\*  $P < 0.001$ ; NS, not significant.

TABLE 4. (a) Eigenvalues of the correlation matrix for principal components analysis of the flood regime variables under the leveed scenario. (b) Eigenvectors from principal components analysis of the flood regime variables under the leveed scenario.

a) Eigenvalues			
Axis	Eigenvalues	Proportion of variance explained	Cumulative variance explained
1	4.58	0.76	0.76
2	1.32	0.22	0.98

b) Eigenvectors		
Flood regime variable	Axis 1	Axis 2
Flood events	0.46	-0.17
Growing season flood events	0.46	-0.16
Days flooded	0.44	-0.26
Growing season days flooded	0.44	-0.26
Shear stress	0.32	0.61
Unit stream power	0.29	0.66

Note: Flood regime variables are described in Table 2.

## DISCUSSION

### *How have flood-control levees influenced the flood regime of the Wisconsin River?*

In the U.S., flood-control levees are designed primarily to restrict overbank flooding, reduce public-

safety hazards, and make floodplain areas available for other land uses. Levees can cause a variety of unintended effects, however. Levees can increase flood heights (Kazmann 1972, Belt 1975, Pitlick 1997); although increases in flood stage can also be caused by navigation works (Belt 1975) and can be difficult to distinguish from land-use changes and long-term trends in precipitation (Knox 2000). Our results confirm some and contradict other reported effects of levees. Our results also contrast natural levels of variability in floods with variability caused by flood-control levees.

The area flooded increased greatly after levee removal (Fig. 3). Due to the morphology of the Wisconsin River floodplain and channel, increases in area inundated leveled off beyond the 25-yr event. After the entire floodplain is inundated, increased discharge resulted in a deeper, not more spatially extensive event. The large size of the inundated area also explains the modest increases in flood height. The broad ecological effects of changes in area inundated due to levees are largely unknown as ecological consequences of changes in flood width have only begun to be explored (Power et al. 1995a, b, Stanley et al. 1997, Yin 1998).

Flood stage was not greatly influenced by levees, and increased on the order of centimeters (Fig. 4). In general, levees constrict a river's width and typically

TABLE 5. Results of stepwise multiple regression ( $P < 0.05$ ) using ranks of the dependent variables.

Dependent variables	Independent variables (partial $R^2$ )	Model $R^2$
Flood-intolerant species		
Overall		
Abundance	Elevation (0.20), Axis 1 (0.18), Axis 2 (0.07), Distance (0.04)	0.48
Basal area	Axis 1 (0.20), Axis 2 (0.14), Distance (0.05), Elevation (0.03)	0.42
IV	Axis 1 (0.16), Axis 2 (0.12), Elevation (0.04), Distance (0.03)	0.35
Adult ( $\geq 25$ cm dbh)		
Abundance	Distance (0.11), Axis 1 (0.05), Axis 2 (0.05)	0.21
Basal area	Distance (0.11), Axis 1 (0.05), Axis 2 (0.05)	0.22
IV	Axis 1 (0.10), Axis 2 (0.07), Distance (0.04)	0.21
Sapling (2.5–5 cm dbh)		
Abundance	Elevation (0.18), Axis 1 (0.16)	0.34
Basal area	Elevation (0.18), Axis 1 (0.16)	0.34
IV	Elevation (0.16), Axis 1 (0.12)	0.28
Flood-tolerant species		
Overall		
Abundance	Axis 1 (0.19), Distance (0.09)	0.28
Basal area	Distance (0.18), Axis 1 (0.08)	0.27
IV	Axis 1 (0.22), Distance (0.10), Axis 2 (0.02)	0.34
Adult ( $\geq 25$ cm dbh)		
Abundance	Axis 1 (0.10), Distance (0.03)	0.12
Basal area	Axis 1 (0.10), Distance (0.02)	0.13
IV	Axis 1 (0.08), Distance (0.02), Elevation (0.02)	0.13
Sapling (2.5–5 cm dbh; <i>F. pennsylvanica</i> only)		
Abundance	Elevation (0.04), Axis 2 (0.04)	0.08
Basal area	Elevation (0.04), Axis 2 (0.04)	0.08
IV	Axis 2 (0.04), Elevation (0.03)	0.07

Notes: Variables are listed in order of amount of variation explained. Flood-intolerant species include *Quercus velutina* and *Q. ellipsoidalis*. Flood-tolerant species include *Acer saccharinum* and *Fraxinus pennsylvanica*. In the case of flood-tolerant saplings, only data for *F. pennsylvanica* are included. PCA axis 1 represents flood frequency, duration, and physical force, whereas axis 2 distinguishes between flood frequency and duration vs. the physical force of the 100-yr flood (i.e., shear stress and unit stream power).

TABLE 6. Results of logistic regression using ranks of the dependent variables.

Dependent variable (presence/absence)	Independent variables (sign of coefficient)	Wald $\chi^2$	P	Model pseudo $R^2$
Flood-intolerant species	Axis 1 (-)	10.89	0.0010	0.50
	Axis 2 (-)	6.48	0.0109	
	Distance (+)	5.71	0.0169	
	Elevation (-)	5.59	0.0181	
Flood-intolerant adult ( $\geq 25$ cm dbh)	Axis 1 (-)	4.37	0.037	0.35
Flood-intolerant sapling (2.5–5 cm dbh)	Axis 1 (-)	6.25	0.0124	0.34
	Elevation (-)	10.50	0.0012	
Flood-tolerant species	Distance (-)	7.8065	0.0052	0.36
Flood-tolerant adult ( $\geq 25$ cm dbh)	Axis 1 (+)	4.02	0.0451	0.17
Flood-tolerant sapling (2.5–5 cm dbh; <i>F. pennsylvanica</i> )	Elevation (-)	5.19	0.0227	0.14

Notes: Variables are listed in order of amount of variation explained. Flood intolerant-species include *Quercus velutina* and *ellipsoidalis*. Flood-tolerant species include *Acer saccharinum* and *Fraxinus pennsylvanica*. In the case of saplings, only data for *F. pennsylvanica* are included. PCA axis 1 represents flood frequency, duration, and physical force; whereas axis 2 distinguishes between flood frequency and duration vs. the physical force of the 100-yr flood (i.e., shear stress and unit stream power).

result in higher stages for a given discharge (Pitlick 1997). For perspective, similar models along the Mississippi suggest a 1-m lowering of stage (for a given discharge) after the removal of all agricultural levees, assuming all areas remain farmland. Floodplain vegetation would make the stage decrease  $< 1$  m (U.S. Army Corps of Engineers 1995). Along the Wisconsin, the levees are not always directly adjacent to the channel (Fig. 1), as are mainline levees. Instead, levees are set back from the channel into the floodplain, allowing

some overbank flooding while producing only a very modest change in flood stage. The very slight increases in flood stage due to the setback design of the levees are, in fact, fundamental to interpreting this research.

Overbank flood velocities at the hydrologic cross sections were altered slightly by levees; however, the impact of levees appears to be minor relative to natural sources of variability among different river cross sections. Differences in velocity between levee and levee-removal scenarios at a given cross section were much

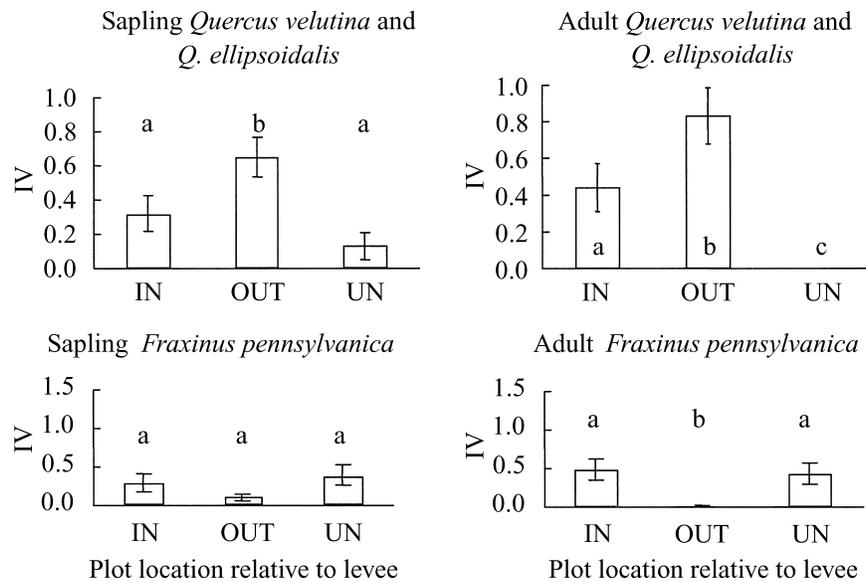


FIG. 8. Influence of levees on the importance values of different species according to size classes representing saplings and mature trees. Letters indicate significant differences in the ranks of IVs in an ANCOVA accounting for distance from the river and relative elevation of plots. Error bars show  $\pm 1$  SE. Plot location abbreviations are: IN, inside levees ( $n = 34$ ); OUT, outside levees ( $n = 33$ ); UN, unleveed areas ( $n = 33$ ).

lower than differences in velocity among cross sections or differences due to increasing discharge (Fig. 5). Flood velocity is greatly influenced by channel constriction (and concomitant increases in the depth of flow) that can vary greatly along a reach. Cross section 33, for example, has a bluff constraining flow on the north bank (Fig. 1), explaining the higher flood velocities at this cross section (Fig. 5). Higher discharges increased velocity more at a given cross section than did the presence of levees. As summarized by Pitlick (1997), studies by the Corps of Engineers report that a greater change in velocity occurs going from low to moderate discharge than from moderate to high discharge. Thus, the effect of different levee configurations on flood velocity might be greatest for floods of moderate return interval (Pitlick 1997).

Obviously, the effects of levees on flood velocity are greatest in areas outside of levees where flow velocities are nonexistent except when levees are overtopped. However, differences in flood velocity between areas inside levees and those same areas when levees are removed are minor compared to natural levels of variability in velocity upstream and downstream areas, and may be ecologically insignificant. In terms of sediment transport, flow velocities of 0.18 to 0.20 m/s are capable of moving sand and overbank flow velocities only rarely approach this amount, even during large floods. As such, levees may influence flow velocities enough to alter patterns of seedling establishment on sandy substrates through scouring and deposition but it is likely that such effects would be primarily confined to the main channel where flow velocities were generally higher (1.07–1.38 m/s). The overbank flow velocities reported here are unlikely to cause physical damage to many established adult trees on the floodplain. These low overbank velocities are due to a combination of the setback levees, the large area of floodplain inundated, and the surface roughness of floodplain vegetation.

At the plot level, levees greatly decreased the number of times and number of days that plots outside of levees were flooded (Fig. 6). According to the simulations, plots outside of levees were never inundated, as there were no discharges in the gauged record (from 1935 to 1996) that would overtop (i.e., breach) the levees. However, levee failure (a break in the levee) during the 50-yr flood of 1938 did allow some inundation on the upland side of levees. More interesting, plots inside levees were not flooded significantly more or less than plots in unveeved areas. Again, this is directly related to the relatively minor changes in flood stage we reported, due in large part to the setback nature of these levees.

Irregular downstream patterns in flood power can reflect patterns in valley width as flood power is minimized in wide valleys (Magilligan 1992). Magilligan (1992) found shear stress of the 2-yr flood equaled shear stress of the 500-yr flood only several kilometers

downstream. Few empirical studies have directly looked at spatial characteristics of stream power, despite its importance to erosion, sediment transport and sediment storage (Lecce 1997b, Knighton 1999). Levees caused a sharp increase in the number of plots with 0 shear stress and power (in areas outside levees), due to lack of any inundation during the 100-yr-flood event, altering the spatial pattern of shear stress and unit stream power on the landscape. Flood power was actually lower inside levees than in unveeved areas (Fig. 6), which is may be due to similar widths of the cross sections in these two areas (i.e., the leveed areas were not extremely constricted as compared to unveeved areas).

Overall, the patterns of flooding outside of levees were highly altered throughout the period of record. However, few differences in the flood regime between unveeved area and areas inside the levees were evident, primarily due to the setback position of the levees.

#### *Have flood-control levees influenced the distribution of floodplain tree species?*

Changes in disturbance regimes often result in substantial alterations to biotic communities and landscape structure (Pickett and White 1985, Glenn-Lewin et al. 1992). Flooding can affect vegetation by causing anaerobic soil conditions, mechanical breakage of plants, and erosion or deposition of alluvium (Hupp 1988, Bendix 1997). Thus, flood-regime alterations due to levees may affect the composition and structure of forested floodplain communities by multiple mechanisms. We determined that the patterns of floodplain vegetation did indeed mimic the changes in the flood regime.

The importance values of select floodplain tree species outside of levees differed from areas inside levees and completely unveeved areas. Outside of levees we found increases in the IVs of the flood-intolerant *Q. velutina* and *ellipsoidalis*, and decreases in the flood-tolerant *A. saccharinum* and *F. pennsylvanica* (Fig. 7). This directly corresponds to the decrease in flooding on the plots outside of levees (Fig. 6). Similarly, along the Upper Mississippi, Yin (1998) found forest stands behind mainline levees to be currently dominated by the less flood-tolerant pin oak (*Quercus palustris* Muenchh., a species less common in the nineteenth century).

Further evidence that levees have had an influence on vegetation is the fact that the IVs of several species (*A. saccharinum*, *F. pennsylvanica*, *Q. velutina*, and *Q. ellipsoidalis*) were highly correlated with the simulated modern levee regime (Table 3) and did not correlate well with the simulated levee-removal flood regime. This suggests that their distributions reflect the flood regime associated with the contemporary configuration of levees, and are not relicts of the flood regime that dominated before levee construction.

We found a strong similarity in the floodplain vegetation between the unveeved areas and areas inside

(riverward) of levees. We detected no differences in the IVs of the flood-tolerant *A. saccharinum* and *F. pennsylvanica* (Fig. 7), likely because the flood regime in these two areas was similar. *Quercus velutina* cannot withstand flooding for even short periods. *Acer saccharinum* is flood tolerant and can survive flooding of 1–3 mo during the growing season as its root system is dormant during flooded periods. *F. pennsylvanica* is even more flood tolerant as trees can withstand flooding for two or more growing seasons and exhibit good adventitious or secondary root growth during flooding (Teskey and Hinckley 1977, Loucks 1987). Johnson et al. (1976) found the maximal growth rates and diameters of *F. pennsylvanica* in areas that often had ponded water. In summary, the duration and frequency of floods was similar between unleveed areas and plots inside levees and thus, the distribution of several dominant floodplain trees was similar between these two areas.

Interestingly, not all flood-tolerant species responded similarly to levees; the IVs of the flood-tolerant *B. nigra* did not show differences among areas inside, outside, or in unleveed areas, nor did the flood-tolerant *Q. bicolor*. Flood-tolerant saplings (2.5–5 cm dbh) responded differently than larger adults ( $\geq 25$  cm dbh) as saplings of the more shade tolerant *F. pennsylvanica* showed no difference in abundance between areas inside, outside or unleveed areas.

Certainly other factors not addressed here influence the distribution of floodplain forest species. Changes in soil texture caused by flooding add to the complexity of the relations between hydrology and floodplain forests (Teskey and Hinckley 1977, Frye and Quinn 1979). Soil pH, organic matter, Ca, and Mg were important factors governing tree distribution in southeastern Wisconsin forested wetlands (Dunn and Stearns 1987). Johnson et al. (1976) found soils in *F. pennsylvanica* and *Acer negundo* (box elder) stands to be high in silt and clay content, and found the highest mean density of *Fraxinus* seedlings in stands with intermediate and high nitrate-nitrogen, phosphorus, and potassium levels. Unlike most upland forests, however, the surface soil texture in floodplain forests may change quickly and dramatically. For example, initial terrace deposits in meanders of the Missouri River can be high in sand content, while later deposits may be composed of silt and clay (Johnson et al. 1976). Thus, soil characteristics at the time of overstory sampling may not be indicative of soil conditions during the germination, establishment, and early development of that overstory. Thus, correlations between overstory and soil conditions may be less meaningful than for upland forest communities where soil changes are often more gradual (Johnson et al. 1976).

#### *Conclusions and management implications for large-floodplain rivers*

Although the National Research Council (1992) has identified the development of restoration techniques for

aquatic systems as a research priority, our ability to predict the success of large river restorations remains limited (Gore and Milner 1990). Undisrupted riverine systems are rare, particularly in the Northern Hemisphere. As such, key components regulating pristine large river systems are difficult to recognize (Bayley 1995), complicating the determination of what constitutes an ecologically “healthy” river (Karr et al. 1986, Steedman 1994, Meyer 1997). Our ability to understand large rivers is further complicated by the geomorphic differences among rivers. Consider the varied geomorphic and vegetative responses of rivers to dams (Ligon et al. 1995, Scott et al. 1996, Stanford et al. 1996, Friedman et al. 1998, Johnson 1998). Dams can either cause dramatic increases or decreases in riparian vegetation depending on the geomorphic type of a river (e.g., braided, meandering, or anastomosing) and the type and operation of the dam (e.g., flood control, hydroelectric power, recreation, or irrigation). The effects of simultaneous, different modifications can be even more difficult to distinguish. Lastly, due to the scale and expense of such operations (Kern 1992), restoration of large rivers has been extremely rare (Regier et al. 1989).

Our results suggest that floodplain areas inside levees are not extremely different from unleveed areas in terms of flood stage and velocity, frequency and duration of inundation, and composition of several floodplain tree species along the Wisconsin River. These similarities are closely linked to the characteristics of setback levees. The setback levees caused minimal increases in flood stage for a given discharge, and consequently, no increase in the frequency and duration of flooding inside levees, resulting in similar vegetation inside levees as compared to unleveed areas. Areas outside levees, however, differ greatly in terms of the flood regime and some species of floodplain trees.

These results may suggest a compromise whereby a system of setback levees can maintain “natural” floodplain vegetation composition while also allowing some flood control. This approach is also extremely relevant to the “string-of-beads” restoration concept (Rasmussen 1994) that essentially states that not all of a floodplain must be reopened to natural flooding to derive valuable ecosystem services or restore valuable floodplain wetland habitat. The “beads” refer to patches of wetlands caused by periodic flooding in the low-lying areas, which are most subject to natural depositional and scouring processes (Galat et al. 1998). Such select areas of floodplains can be restored by taking advantage of the natural geomorphic processes that will help rejuvenate such areas. Focused experimental flooding in already flood-prone areas combined with “passive approaches” to restoration and management can be practical from a logistic, monetary, and ecological standpoint (Sparks 1998). Passive approaches refer to non-structural techniques, such as little to no channel manipulations or drawdowns, but rather letting processes

such as succession and hydraulic forces of the river help restore such areas. This idea can be used to help guide the construction and removal of levees. We recommend where levees are necessary, the more area inside the setback levees relative to the upland side of levees, the better. Furthermore, when considering levee-removal, removal of mainline (directly adjacent to the channel) levees should be a higher priority than setback levees.

Setback levees, when accompanied by decreases in flood velocity and stage (as compared to a situation with mainline levees) can also help reduce damage to levees during floods. When flow velocity is reduced, the shear force of moving water is reduced substantially (Beasley et al. 1984). Furthermore, woody vegetation in setback areas might also protect levees (Shields and Gray 1993, Dwyer et al. 1997) by creating drag and reducing flow velocity. After controlling for floodplain width, Dwyer et al. (1997) found that primary levees along the Missouri that did not fail in the 1993 floods had wider woody corridors than failed levees. As the width of the woody corridor increased, both the number of and size of breaks decreased (Dwyer et al. 1997). To reduce the number of levee failures and the severity of damage, Dwyer et al. (1997) recommend woody corridors ~100 m wide (at least 300 feet). Note, however, that adding vegetation to a previously unvegetated area (e.g., an agricultural field) may increase flood stage (U.S. Army Corps of Engineers 1995), potentially offsetting some of the benefits of the setback levees by increasing roughness, slowing velocity, and potentially creating new bottlenecks. However, all such determinations rely heavily on assumptions regarding overbank roughness (U.S. Army Corps of Engineers 1995) and should be evaluated on a case-by-case basis.

Our results suggest that levees have a greater impact on larger magnitude events. Here, we determined that levees had little impact on flood stage, area inundated, and flood velocity for smaller magnitude events—but greater differences were evident for larger magnitude events. However, it must be noted that these results assume no levee breach or failure, the risk of which likely increases for larger magnitude events. Thus, management and restoration schemes may be different for different sized events (e.g., high and low levees for different-sized spring and fall floods, Sparks 1998). The greater impact that levees have on larger magnitude events suggests that the response of river-floodplain systems to levees might be very different in rivers where flood peaks have been dampened (e.g., in channels influenced by dams, such as the Wisconsin River example here) vs. rivers where peak flows have been augmented (e.g., due to changes in upland hydrology as in Fitzpatrick et al. 1999). The effect of levees on larger magnitude events might also be important in terms of global climate change as transition periods of rapid climate change have been associated with higher frequencies of large and extreme floods (Knox 2000).

Our results also suggest that the influence of levees would not have been detected if only certain species or young individuals of certain species were surveyed. Recall, that not all species of flood-tolerant trees responded to the presence of levees (e.g., *Betula nigra* and *Quercus bicolor*). Also, saplings of the flood-tolerant *Fraxinus pennsylvanica* were not influenced by levees, although larger individuals ( $\geq 25$  cm dbh) were sensitive to this alteration. A catchment-based approach that moves away from emphasis on one or few species towards management that preserves the dynamics of a geomorphologically active system (Ligon et al. 1995) is recommended. We must consider changes in inundation patterns, velocity, and power, as well as changes in individual species.

Despite the significance of flooding in riparian zones and the widespread human alteration of flood regimes, floods are not as well understood as other disturbances (Miller 1995). In particular, the ecological consequences of flood-control levees have largely been ignored relative to other flood regime disruptions such as dams. Furthermore, many disturbances are heterogeneous across a landscape both in terms of where they occur and on the severity of their effects (Runkle 1985, Foster 1988, Dale 1991), and this is certainly true of floods. However, the relative importance of anthropogenic alterations in influencing the variability and heterogeneity of catastrophic disturbances remains largely unknown. This creates additional challenges for devising restoration and management schemes that mimic natural levels of variability in floodplains and other disturbance-driven systems. Our results and recommendations are most relevant to other alluvial, large-floodplain rivers with significant areas of setback levees. Understanding the effects of levees on flood regimes and floodplain vegetation must be undertaken within the context of the geomorphic type of river, type of levee (mainline, setback), and the magnitude of a given flood event relative to the process of interest.

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