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Channelization and floodplain forests: Impacts of accelerated sedimentation and valley plug formation on floodplain forests of the Middle Fork Forked Deer River, Tennessee, USA

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Abstract

We evaluated the severe degradation of floodplain habitats resulting from channelization and concomitant excessive coarse sedimentation on the Middle Fork Forked Deer River in west Tennessee from 2000 to 2003. Land use practices have resulted in excessive sediment in the tributaries and river system eventually resulting in sand deposition on the floodplain, increased overbank flooding, a rise in the groundwater table, and ponding of upstream timber. Our objectives were to: (1) determine the composition of floodplain vegetation communities along the degraded river reach, (2) to isolate relationships among these communities, geomorphic features, and environmental variables and (3) evaluate successional changes based on current stand conditions. Vegetation communities were not specifically associated with predefined geomorphic features; nevertheless, hydrologic and geomorphic processes as a result of channelization have clearly affected vegetation communities. The presence of valley plugs and continued degradation of upstream reaches and tributaries on the impacted study reach has arrested recovery of floodplain plant communities. Historically common species like *Liquidambar styraciflua* L. and *Quercus* spp. L. were not important, with importance values (IV) less than 1, and occurred in less than 20% of forested plots, while *Acer rubrum* L., a disturbance-tolerant species, was the most important species on the site (IV = 78.1) and occurred in 87% of forested plots. The results of this study also indicate that channelization impacts on the Middle Fork Forked Deer River are more temporally and spatially complex than previously described for other river systems. Rehabilitation of this system necessitates a long-term, landscape-scale solution that addresses watershed rehabilitation in a spatially and temporally hierarchical manner.

Keywords: Bottomland hardwood forests; Channelization; Valley plugs; Sedimentation; Erosion; Floodplain vegetation; Degradation; Tennessee rivers

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1. Introduction

Riparian forested wetlands are of global importance for the functions and values they provide. The timing, depth, and duration of flooding are the primary determinants of plant species composition and productivity (Huffman and Forsythe, 1981; Dollar et al., 1992; Robertson et al., 2001). In addition, light availability and the types and rate of sediment deposition can also strongly influence tree species composition in these forests (Hodges, 1997; Hall and Harcombe, 1998). As freshwater management becomes increasingly important to growing urban and rural demands, the need for research related to the effects of river management on flora and fauna worldwide increases (Jackson et al., 2001). Channelization is a river channel modification often utilized in low-gradient streams to increase the competence of the river through deepening, widening, shortening, and straightening the channel. Channelization affects the hydrology of the adjacent floodplain forest at multiple spatial and temporal scales (Shankman, 1996). In upstream reaches, floodplain forests may become drier as the new ditch funnels water off of the floodplain and entrenchment of the river system decreases the height of the water table (Marston et al., 1995; Shankman, 1996). In contrast, flooding in lower reaches of the watershed is more frequent than pre-channelization but flood events are of shorter duration (Shankman and Pugh, 1992; Shankman, 1996). Temporally, the effects of channelization on the floodplain forest may change as channel incision occurs along the ditch and adjacent tributaries, and lower reaches begin to aggrade as the result of increased sedimentation (Schumm et al., 1984; Wyzga, 2001).

In the Southeastern Coastal Plain and loess belt of the Lower Mississippi River Alluvial Valley (LMAV), USA, erosion and sedimentation associated with channelization can be particularly severe. Loess deposits originating during the mid-to-late Pleistocene cover an extensive portion of the LMAV in Tennessee and Mississippi (Bettis et al., 2003). Loveland, Roxana, and Peoria loess deposits vary from <1 to 20 m, with thickness of deposits decreasing from the Mississippi River eastward (Bettis et al., 2003). Loess soils are agriculturally productive, but highly erosive. Poor agricultural practices throughout the 1800s and early 1900s in this hilly region have led to erosion and, in some cases, removal of the loess caps to expose underlying, unconsolidated Coastal Plain sands (Happ et al., 1940; Hupp, 1992; Saucier, 1994). Saucier (1994) contends that erosion occurring in the loess uplands of west Tennessee over the past 150 years equals or exceeds the erosion occurring in the last several thousand years, and is directly related to a 20-fold increase in sedimentation from gullies in the region. Subsequent channelization allowed for the movement of coarse sediments from uplands, gullies, and associated tributaries into the main channel of many of the river systems throughout the Coastal Plain. Accelerated sedimentation associated with erosion and channelization in alluvial systems has resulted in the formation of atypical geomorphic features, including valley plugs (Happ et al., 1940) (Fig. 1).

Valley plugs, as defined by Happ et al. (1940), develop as coarse sediments aggrade in response to a channel irregularity (i.e., tributary confluence, reduction in stream gradient, debris jam). Sediment aggrades in the riverbed, diverting water flow and initiating increasing amounts of sediment deposition. Over time, aggradation occurs to the extent that the entire river channel is blocked by accumulated debris and coarse sediments. This positive reinforcement cycle results in aggradation within the riverbed beginning at the head (downstream end) of the valley plug and extending upstream for a variable distance (Happ et al., 1940; Diehl, 2000) (Fig. 1). Unless the sand source is removed, the valley plug will continue to increase in size and extend the aggrading streambed further upstream. During subsequent flood events, floodwaters spread across the floodplain at the upstream end of the valley plug, scouring out anastomosing channels that reconnect to the stream below the head of the valley plug. In addition, large amounts of sand are deposited in the floodplain at the upstream end of the plug when the water leaves the streambed and spreads across the forest floor. Excessive sediment deposition can also lead to large height increases in the natural levee, preventing adequate drainage of the floodplain and ponding large areas of timber. Breaks in the natural levee, or in the spoil bank, can lead to sand splays on the floodplain (Happ et al., 1940).

Interest in the vegetation response to these changes in channel geomorphology is relatively recent.

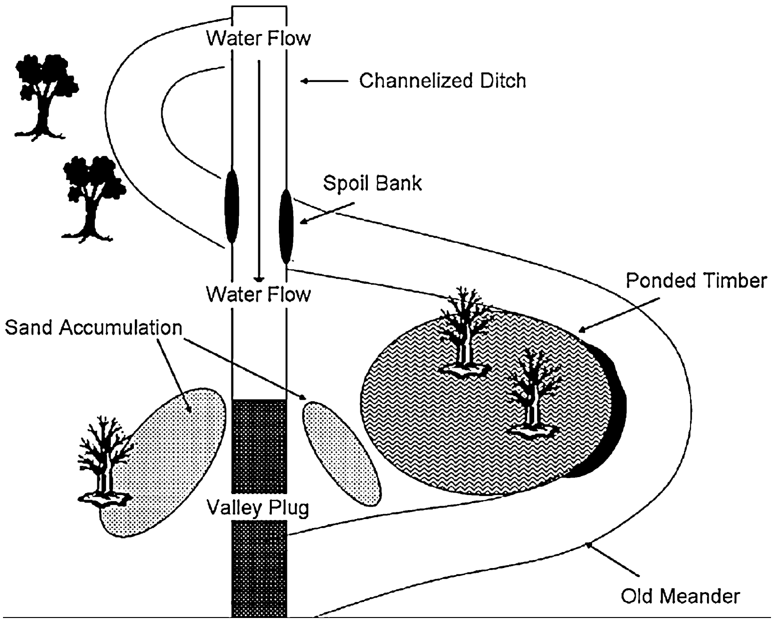

Fig. 1. Generalized map of alluvial system affected by excessive sedimentation and valley plug formation. Atypical geomorphic features are indicated.

Undisturbed floodplain forests in west Tennessee typically include mixtures of several species, including sweetgum (*Liquidambar styraciflua*), American elm (*Ulmus americana*), green ash (*Fraxinus pennsylvanica*), overcup oak (*Quercus lyrata*), nuttall oak (*Quercus nuttalli*), willow oak (*Quercus phellos*), and cherrybark oak (*Q. falcata* var. *pagodaefolia*) (Hupp, 1992). Post-channelization communities differ, however, depending upon the time since channelization and the depositional environment (Simon and Hupp, 1987; Hupp, 1992; Wilder, 1998). Simon and Hupp (1987) and Hupp (1992) developed models to describe recolonization patterns of riparian vegetation following channelization. Their efforts, however, concentrated primarily on the vegetation immediately adjacent to the streambank (within 50 m of the river channel), and not on the active floodplain or beyond. Additionally, their models focused on the recovery of bank stability following channelization, and valley plug formation was beyond the scope of their investigation. Nevertheless, their model of riparian recovery patterns provides a base of knowledge from which to begin examination of vegetation patterns as they relate to valley plug formation.

In this study, we investigate the response of floodplain vegetation to channelization and the subsequent formation of valley plugs on a 9 km reach of the Middle Fork Forked Deer River in west Tennessee, a contributor to the Obion-Forked Deer River system. The study reach was selected because of its extreme state of degradation, and because of the desire to restore the selected reach. Our objectives were to: (1) describe the composition of floodplain vegetation communities along the degraded river reach, (2) determine the major environmental factors affecting forest composition, including the relationship among forest communities and geomorphic formation as defined by Happ et al. (1940), and (3) to evaluate future successional changes based on current stand conditions.

2. Study site

The Middle Fork Forked Deer River is a component of a larger system, the Obion-Forked Deer River system, which drains directly into the Mississippi River. The Obion-Forked Deer River system occupies approximately 11% of Tennessee's land area and includes all or portions of 14 counties (Obion-Forked Deer River Basin Authority, 1983). The Middle Fork Forked Deer River watershed drains portions of six counties: Henderson, Carroll, Madison, Gibson, Crockett, and Dyer, and is approximately 77 km long and 16 km wide (U.S. Army Corps of Engineers, 1970). The approximate drainage area encompassing the study site and areas just downstream is 546 km^2.

The U.S. Army Corps of Engineers began to channelize the river system in the early 1900s in an attempt to control flooding, aid in drainage, and to enhance agricultural production (U.S. Army Corps of Engineers, 1970; Hill, 1976; Turner et al., 1981). Since that time, the majority of the Obion-Forked Deer River system has been channelized, including the main channel, tributaries, and the entire reach evaluated in this study.

Flooding is frequent during the late fall-spring months, and is associated with local rain events. Peak streamflows in the Middle Fork Forked Deer River basin occur during the months of December–May (U.S. Geological Survey, 2002). Peak stream flow during flood events may reach levels as high as 245 m^3/s (U.S. Geological Survey, 2002). Flood duration tends to be relatively short, with large magnitude floods seldom lasting more than 9 days (U.S. Army Corps of Engineers, 1970).

The study reach of the Middle Fork Forked Deer River lies in Madison and Carroll Counties, Tennessee and begins at Highway 70 southwest of Huntingdon, continuing to its intersection with Christmasville Road southeast of Milan. The majority of the study site is privately owned, and the floodplain is used for agriculture, timberland, and recreational activities like hunting and fishing.

Soils are composed of Coastal Plain sediments, recent alluvium, and Pleistocene loess deposits (U.S. Department of Agriculture, 1978, 1984). Soils include coarse-silty, mixed, acid, thermic Aeric Fluvaquents; coarse-silty, mixed, acid, thermic Aquic Udifluvents; coarse-silty, mixed, acid, thermic Typic Fluvaquents of the Falaya–Waverly–Collins associations (U.S. Department of Agriculture, 1978). These soils are typically poorly drained soils found on the river floodplains. They tend to be extremely friable, fertile soils suitable for agriculture. Soil surveys conducted in 1978 by the U.S. Department of Agriculture state that "included with [these soils] in mapping were small areas of very sandy soils." Soils found in the uplands within the Middle Fork Forked Deer watershed are generally gently sloping, highly eroded fine-silty, mixed, active, thermic Typic Hapludalfs; fine-silty, mixed, thermic Typic Paleudalfs; fine-loamy, siliceous, thermic Typic Paleudults of the Memphis–Lexington–Smithdale associations (U.S. Department of Agriculture, 1978).

3. Methods

3.1. Vegetation composition

We used a stratified random sampling design to inventory the vegetation on the study site. Stratifications were based on broad geomorphic features as described by Happ et al. (1940). The geomorphic features, identified through intensive and extensive field surveys, included sand accumulation, ponded timber, channelized ditch, elevated streambed, anastamosing river, and old river meander characteristics (Fig. 1). Landowner permission to access the sites and land use activities also influenced the selection of sample sites. For example, sites where recent timber harvesting or other land clearing activities were known to have occurred were avoided. A total of eight separate stands were sampled intensively (Table 1).

Within each broad geomorphic feature listed above, a minimum of five 400 m^2 (20 m × 20 m) sampling plots was established at 30 m intervals along transects aligned perpendicular to the channelized study reach, for a total of 61 plots. Transect length varied by forest stand size, geomorphic feature boundaries, and landowner property boundaries.

Table 1
Number of sample plots on the Middle Fork Forked Deer River within each predefined geomorphic feature

Geomorphic feature	Number of plots (*n*)
Sand accumulation	5
Ponded timber	10
Channelized ditch	10
Elevated streambed	11
Anastamosing river	15
Old river meander	10
Total	61

Transects were located at least 50 m from any unnatural edge (e.g., highways, fields) and were spaced 200 m apart in each vegetation association. Within each 400 m^2 plot, diameter at breast height (dbh) of overstory trees (dbh > 5 cm), species composition, relative density, relative frequency of occurrence, and relative size were recorded.

3.2. Elevation and hydroperiod

Elevations were acquired at the center of each 400 m^2 overstory plot. Point elevations within plots and at water-level recorders were obtained using a Topcon Total Station GTS-229. To eliminate the effects of downstream slope, elevations were obtained at the river channel water surface during a low flow period in September 2002, and elevations at plot center were then calculated to reflect elevations relative to the river channel (Smith, 1996).

Continuous water-level recorders were established at or near vegetation transects at four stands to monitor study-site hydrology. Water-level recorders were located at the perceived lowest elevation on the floodplain. The lack of landowner permission prevented the placement of recorders at all sites.

3.3. Soil analysis

Soil samples were acquired at each 400 m^2 plot. At a minimum of one point in each 400 m^2 plot, 1 m deep columns of soil were extracted and field observations of color (using a Munsell color chart), texture (by feel), structure and general morphology (by visual assessment) were recorded (Dollar et al., 1992). At each of four quadrants, a 25 cm column of soil was extracted using a tubular soil probe (Smith, 1996; Grace et al., 2000). The four samples in each 400 m^2 plot were homogenized, air dried, and sent to A&L Laboratories in Memphis, TN where they were analyzed for texture, pH, macro- and micronutrients, and nitrogen content.

3.4. Analysis of environmental factors and forest composition

To characterize relationships between plant communities and site geomorphology, we used multivariate cluster analysis and ordination techniques. Cluster analysis was performed using the ordination software PC-ORD (MJM Software Design, 1999) to identify vegetation associations. Prior to cluster analysis and ordination, rare species (species occurring in less than 5% of plots) were eliminated from the dataset (Grace et al., 2000).

Hierarchical analysis was based on Euclidean distance measures and Ward's minimum-variance method (McCune and Mefford, 1995; McCune and Grace, 2002; Burke et al., 2003). The resulting dendrogram was broken into clusters with an average of 90% information remaining (distance = 0.9) (Burke et al., 2003). The identified vegetation associations were evaluated using a multi-response permutation procedure (MRPP) (Grace et al., 2000). Relationships between individual species and the identified vegetation associations were calculated using indicator species analysis in PC-ORD (McCune and Grace, 2002), which combines species abundance with faithfulness of occurrence within each community type (Burke et al., 2003). The significance of indicator species ($P \leq 0.05$) was calculated using Monte Carlo techniques (Dufrêne and Legendre, 1997). Indicator species were verified by calculating the mean relative basal area for species within clusters to determine the dominant species within each cluster.

The ordination of plots was performed using nonmetric multidimensional scaling (NMMS) in the software package PC-ORD (MJM Software Design, 1999). The NMMS ordination was performed with Sorenson distance measures using random starting configurations selected by the computer. Initially, species associations identified in overstory cluster analysis were used as group identifiers during ordination. The Monte Carlo tests, stress level (unexplained variation), and instability values were used to determine the appropriate number of dimensions for ordination (McCune and Grace, 2002). We determined the relationship between axis scores and environmental variables using correlation analysis, and the total variation explained by all axes was calculated. Results from the NMMS analysis were verified using a standard ANOVA between means of important environmental variables within cluster groups.

3.5. Forest succession

To determine forest succession patterns, we used a combination of diameter distribution plots (Johnson and Bell, 1976; Conner et al., 1981) and dendrochronology techniques (Stokes and Smiley, 1968). Virtually all stands were dominated by red maple, thus dendrochronology was used to help determine when environmental conditions changed to allow for the establishment of red maple. Five plots were randomly selected in each of six stands for intensive study. In the remaining two stands, a total of two and three plots each were randomly sampled. In each plot, one tree from each of four diameter classes was selected for coring. Because of the dominance by red maple on the study site, red maple received the primary focus. Because of their current scarcity but past abundance, all oaks (*Quercus* spp.) in the selected plots were cored, as well as remnant trees of various species. Two cores per tree were extracted using Hagloff increment borers (Abrams et al., 1995). Cores were air dried at room temperature and examined using a dissecting microscope. Verification of ring counts was obtained from the dendrochronology laboratory at the University of Tennessee, Knoxville.

Table 2
Tree species on the Middle Fork Forked Deer River study site listed by species name, common name, and four-letter botanical code

Species	Common name	Code
Acer negundo L.	Box elder	ACNE
Acer rubrum L.	Red maple	ACRU
Acer saccharinum L.	Silver maple	ACSA
Alnus serrulata (Ait.) Willd.	Hazel alder	ALSE
Betula nigra L.	River birch	BENI
Carpinus caroliniana Walt.	American hornbeam	CACA
Carya spp.	Hickory	CASP
Cornus amomum Mill.	Swamp dogwood	COAM
Diospyros virginiana L.	Persimmon	DIVI
Fraxinus pennsylvanica Marsh.	Green ash	FRPE
Liquidambar styraciflua L.	Sweetgum	LIST
Liriodendron tulipfera L.	Yellow-poplar	LITU
Morus rubra L.	Red mulberry	MORU
Nyssa aquatica L.	Water tupelo	NYAQ
Nyssa sylvatica Marsh.	Swamp tupelo	NYSY
Platanus occidentalis L.	Sycamore	PLOC
Quercus falcata var. *pagodaefolia* Ell.	Cherrybark oak	QUFA
Quercus michauxii Nutt.	Swamp chestnut oak	QUMI
Quercus phellos L.	Willow oak	QUPH
Salix nigra L.	Black willow	SANI
Snag	Snag	SNAG
Taxodium distichum (L.) L.C. Rich.	Baldcypress	TADI
Ulmus spp. L.	Elm	ULSP

4. Results

4.1. Overstory composition

There were 23 tree species present in the overstory and midstory combined, excluding snags (Table 2). Of the 61 plots sampled on the MFFD River floodplain, three contained no overstory tree species. Total tree density of the overstory on the study site was 617 trees ha^{-1}. Total basal area of the overstory on the study site was 59 $m^2\ ha^{-1}$.

Red maple was the most important species across the entire study site, with an importance value (IV 200; relative density + relative basal area) of 78.1. Red maple occurred in 83.4% of total plots sampled on the study site, and 87% of the forested plots sampled (forested plots contained at least one tree). Water tupelo was the only other species with an importance value greater than 20 (IV 200 = 29.76). Historically, common species like baldcypress had importance values less than 20, and oaks and sweetgum had importance values of less than 1 and occurred in less than 20% of the forested plots sampled.

Cluster analysis identified six vegetation groups using the dominant species in the sample plots based on relative basal area and indicator values (Fig. 2). These vegetation groups were not closely associated with specific geomorphic features. Indicator species analysis showed that river birch was the indicator of river birch stands, "snag" was the indicator of snag stands, baldcypress was the indicator of baldcypress stands, red maple was the indicator of red maple stands, water tupelo was the indicator of water tupelo stands, and black willow was the indicator of black willow stands ($P < 0.05$). It is important to note that indicator values utilize relative basal area and % of perfect indication (i.e., the number of times a species occurs in one and only one cluster type) (MJM Software Design, 1999), thus a species can be an indicator species for a particular community type and not be the dominant species in that community. For example, although river birch was the indicator for the river birch stand, the mean relative basal area of red maple ($32.91 \pm 3.47\ m^2\ ha^{-1}$) for plots in the river birch cluster was higher than the mean relative basal area of river birch ($14.80 \pm 3.71\ m^2\ ha^{-1}$). Multiresponse permutation procedures produced a *t*-test statistic of −28.46, and a chance-corrected within-group agreement (A) of 0.5

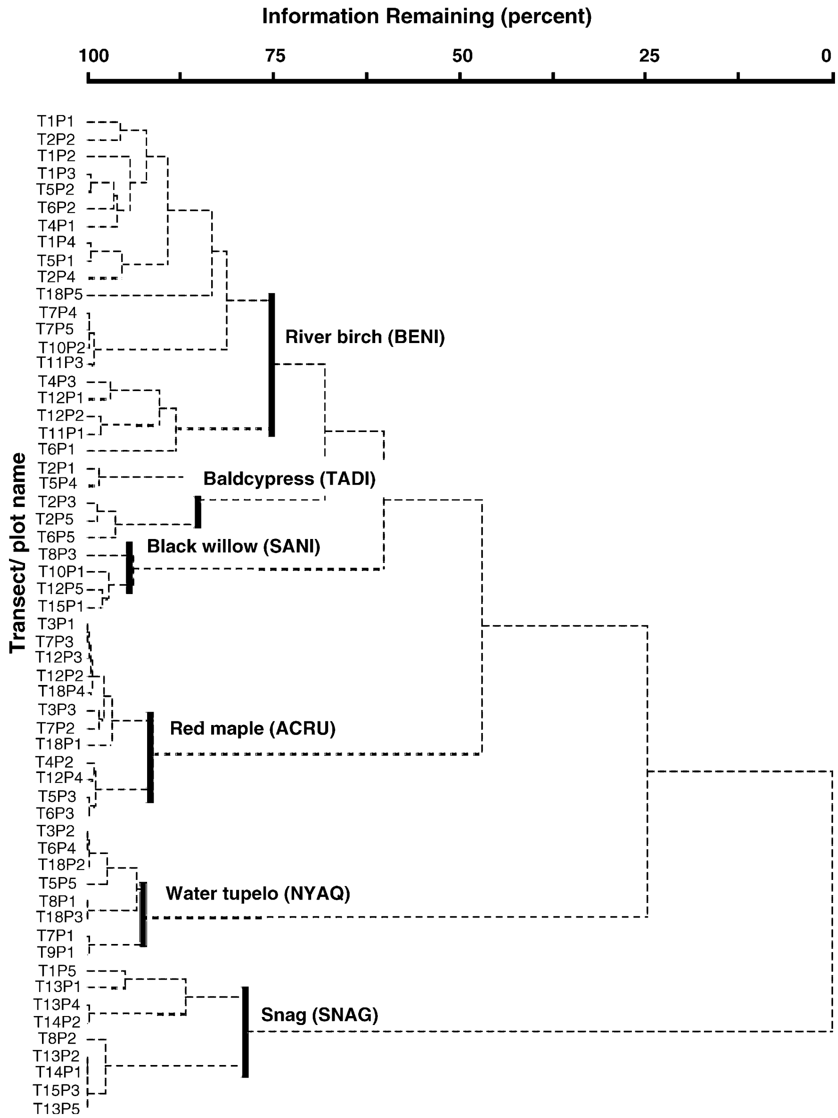

Fig. 2. Dendrogram produced using cluster analysis on importance values for species in each plot.

($P < 0.001$), indicating within-group homogeneity and between-group heterogeneity.

Red maple comprised the highest IV 200 values in the red maple and river birch associations, and the second highest importance values in the water tupelo, black willow, and snag stands (Table 3). In the snag association, red maple had a higher IV 200 than any other living tree species. In the baldcypress association, baldcypress (IV = 72.6) and water tupelo (IV = 57.9) were dominant species followed by red maple (IV = 34.9). Sweetgum and oak species did not have an IV 200 greater than 2.7 in any association.

4.2. Ordination analysis on the overstory

A three-dimensional solution was determined to be the most suitable for this dataset (Fig. 3a–c). The three-dimensional model explained a total of 79.8% of the variation in the data. The first axis explained 18.6% of the total variation, axis two explained 26.4% of the

Table 3
Importance values (IV 200) of species on the Middle Fork Forked Deer River, west Tennessee

Species	Species association					
	ACRU	BENI	NYAQ	SANI	SNAG	TADI
Acer negundo	0.7	12.7	0.6	2.6	2.2	3.3
Acer rubrum	151.5	76.9	30.0	51.6	19.2	34.9
Acer saccharinum	1.2	1.4	0.0	0.0	0.0	0.0
Alnus serrulata	0.0	2.8	1.2	5.1	2.1	1.4
Betula nigra	2.0	26.6	0.0	1.4	0.0	0.0
Carpinus caroliniana	3.2	4.6	0.0	4.9	0.0	0.8
Carya spp.	0.7	0.9	0.0	1.6	0.0	0.0
Cornus amomum	0.3	0.4	0.0	0.0	0.0	0.0
Diospyros virginiana	0.0	0.2	0.0	0.0	0.0	0.0
Fraxinus pennsylvanica	14.1	11.2	0.0	19.2	7.7	1.5
Liquidambar styraciflua	0.4	1.2	0.0	2.7	0.0	0.0
Liriodendron tulipfera	0.0	0.5	0.0	0.0	0.0	0.0
Morus rubra	0.0	1.6	0.0	0.0	0.0	0.0
Nyssa aquatica	5.7	3.8	149.1	0.0	7.5	57.9
Nyssa sylvatica	0.9	0.7	0.0	0.0	0.0	0.0
Platanus occidentalis	2.3	7.1	2.4	2.9	4.0	4.4
Quercus falcata var. *pagodaefolia*	0.3	0.0	0.0	0.0	0.0	0.0
Quercus michauxii	0.0	0.4	0.0	0.0	1.9	2.2
Quercus palustris	0.0	0.5	0.0	0.0	0.0	0.0
Quercus phellos	0.4	0.8	0.0	0.0	0.0	0.0
Salix nigra	3.0	16.7	0.0	89.7	0.0	5.7
snag	6.9	13.7	10.2	10.1	138.4	10.6
Taxodium distichum	0.0	8.6	6.5	5.9	17.1	72.6
Ulmus spp.	6.5	6.7	0.0	2.4	0.0	4.7

IV 200 values are displayed by species associations identified through cluster analysis.

variation, and axis three explained 34.8% of the total variation. Pearson and Kendall correlations were used to relate environmental variables to total axis scores. Buffer pH ($r = 0.388$) was positively correlated with axis one, while organic content ($r = -0.399$) and percent clay ($r = -0.333$) were negatively correlated with axis one. Magnesium was positively correlated with axis two ($r = 0.400$), and relative elevation was negatively correlated with axis three ($r = -0.296$).

4.3. Environment and overstory

Environmental variables were evaluated for the species associations determined through overstory cluster analysis to validate the NMMS ordination results, and to explore differences in environment between associations. The five variables correlated with ordination axes were relative elevation, magnesium, percent clay, organic content, and buffer pH. Measurements of buffer pH are reflections of the physical qualities of the soil, particularly the amount of clays present in the soil that would prevent or enhance the action of lime added to soil to alter the soil pH (Foth, 1984). Measurements of buffer pH are of little biological significance in explaining the spatial extent of vegetation communities (Foth, 1984), so buffer pH values are excluded from further analysis.

Mean relative elevation ($P = 0.008$), magnesium (ppm) content ($P = 0.01$; $x = 137.5 \pm 8.3$ ppm), organic matter content ($P = 0.09$; $x = 1.02\% \pm 0.03$), and CEC differed ($P = 0.07$; $x = 8.8 \pm 0.313$) among species associations (Table 4). The baldcypress association had the highest mean relative elevation and the water tupelo and snag associations had the lowest mean relative elevations. Not surprisingly, mean CEC was negatively correlated with sand content. The mean organic matter content found in this study is a value consistent with a mineral soil (Stanturf and Schoenholtz, 1998).

Mean percent clay content ranged from 26.3 ($\pm$2.56) in the red maple community to 16.0 ($\pm$3.91) in the black willow community, but did not

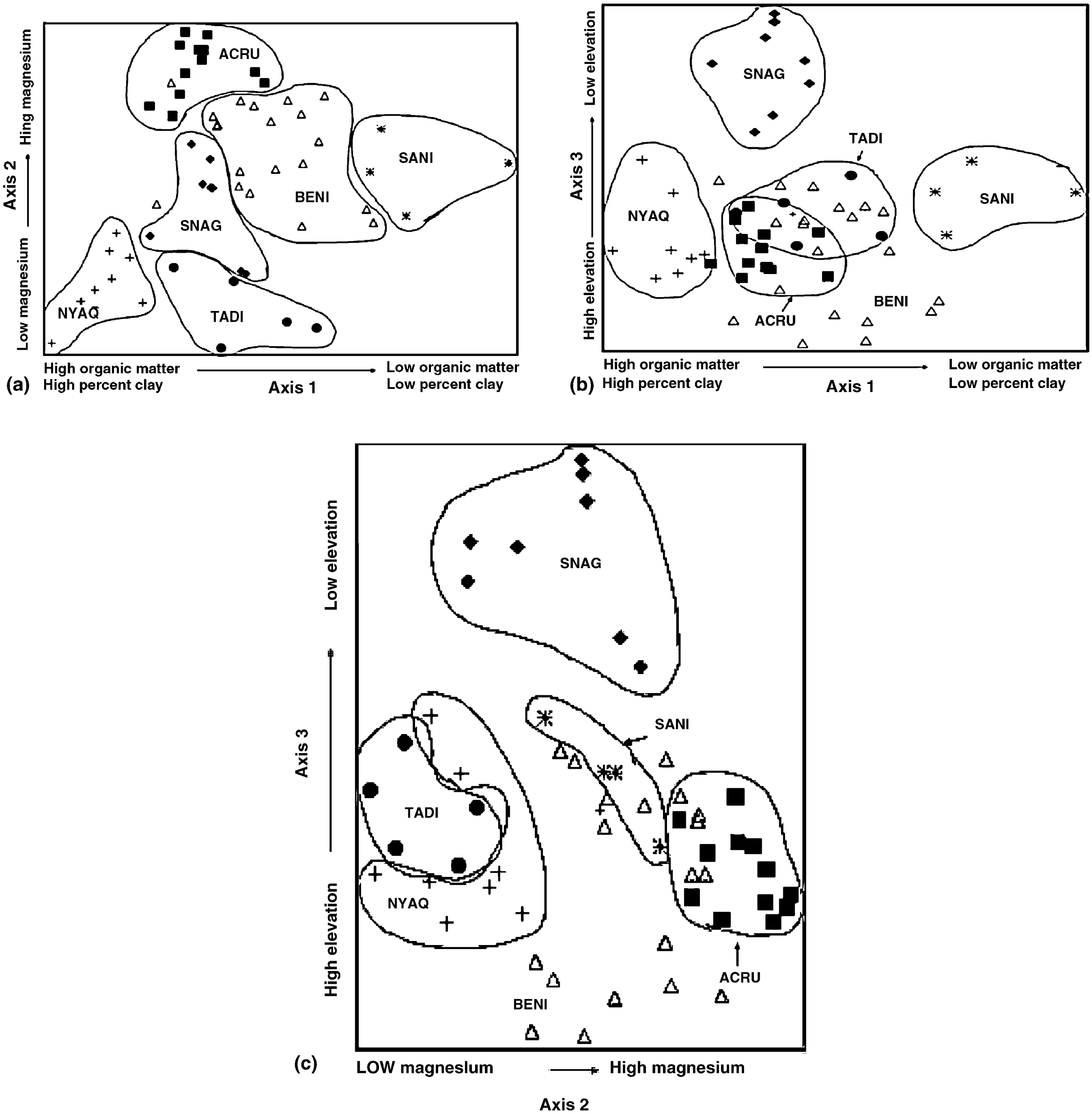

Fig. 3. (a–c) Three dimensional results of NMS ordination on species associations. Environmental variables are labeled on axes 1–3. Species associations are identified by four-letter abbreviations as given in Table 3.

differ ($P > 0.1$). No differences in phosphorous content occurred, but mean phosphorous over all the forested sites appeared to be higher than typical values for alluvial wetlands (Wharton et al., 1982), corresponding to descriptions of increased phosphorous levels, high water turbidity, and low organic matter found in channelized streams (Wilder, 1998). No other environmental variables differed among groups ($P > 0.1$).

While percent clay was the only textural variable that differed among species associations, it is of interest to note that across all forested sites, mean

Table 4
Mean (±1 S.E.) of environmental variables in each species association identified in Table 3

Species association	Soil pH	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	CEC (meq/100 g)	Organic (%)	NO_3-N (mg/kg)	Sand (%)	Silt (%)	Clay (%)	Relative elevation (m)
BENI	4.88 (0.06)	13.41 (1.06)	74.00 (6.10)	633.95 (55.29)	150.40 (12.92) a,b	8.92 (0.51) a,b	0.98 (0.46) b	8.55 (1.14)	28.80 (3.59)	50.55 (2.94)	20.65 (1.75)	0.07 (0.11) a,b
SNAG	4.92 (0.08)	10.89 (1.58)	60.11 (9.10)	457.78 (84.42)	125.22 (19.24) b,c	7.68 (0.76) b	0.96 (0.07) b	4.00 (1.70)	35.00 (5.34)	46.11 (4.39)	18.89 (2.61)	−0.47 (0.16) c
TADI	4.96 (0.11)	12.00 (2.11)	63.80 (12.20)	575.00 (110.58)	111.20 (25.85) b,c	8.70 (1.02) a,b	1.14 (0.09) ab	9.00 (2.28)	24.00 (7.17)	54.80 (5.88)	21.20 (3.50)	0.44 (0.22) a
ACRU	4.88 (0.07)	12.33 (1.36)	84.42 (7.87)	702.08 (71.38)	179.25 (16.69) a	10.28 (0.66) a	1.06 (0.06) a,b	7.67 (1.47)	24.67 (4.63)	49.08 (3.80)	26.25 (2.56)	−0.13 (0.17) b,c
NYAQ	4.79 (0.09)	13.00 (1.67)	68.25 (9.64)	472.00 (87.42)	99.88 (20.44) c	8.69 (0.80) a,b	1.17 (0.07) a	5.00 (1.80)	34.50 (5.67)	42.38 (4.65)	23.13 (2.76)	−0.38 (0.17) c
SANI	4.83 (0.12)	15.75 (2.36)	50.50 (13.64)	363.50 (123.64)	83.50 (28.9) c	6.67 (1.14) b	0.90 (0.10) b	4.50 (2.55)	39.00 (8.02)	45.00 (6.58)	16.00 (3.91)	−0.34 (0.24) b,c

Letters indicate significant differences between associations.

percent silt content (μ = 48.4 ± 1.71) exceeded that of mean percent sand (μ = 29.9 ± 2.10, $P < 0.0001$) and mean percent clay (μ = 21.6 ± 1.05, $P < 0.0001$). Also, overall percent sand increased slightly from downstream to upstream (slope = 2.43, P = 0.06). The results are complicated by the presence of multiple valley plugs and multiple contributors of sediments throughout the system, however, so the apparent pattern may oversimplify the results.

4.4. Diameter distributions forest succession

With the exceptions of the snag and water tupelo associations, red maple was the dominant species in the smallest size class of all associations and it accounted for 55.9% of all stems in this class. Red maple also dominated the 10–19.9 cm size classes of the black willow, river birch, and red maple associations. The majority of red maple stems were <30 cm dbh.

Red maple was the dominant species in all size classes in the red maple and river birch associations. The black willow and baldcypress associations have large relict trees of black willow and baldcypress, respectively, but red maple is the most abundant species in the smaller size classes of the black willow stands. In the baldcypress stands, water tupelo is the dominant species throughout all size classes, although red maple trees <30 cm dbh are relatively abundant.

The mean age of red maple varied from a low of 20.3 ± 3.1 years (n = 4) in the black willow association to 37.5 ± 3.6 in the river birch association. The two oldest red maple trees were 68 years (red maple association) and 73 years (river birch association). The median age of red maple across all sites was 32 years old.

Small sample sizes limit conclusions for other species. Baldcypress ranged from 43 years to 93 years old (n = 4) and water tupelo from 53 years to 90 years old (n = 2). Only three oaks were present in plots sampled for age, and they ranged from 16 to 48 years old.

5. Discussion and conclusion

The results of this study indicate that channelization and subsequent hydrologic and geomorphic changes, including valley plug formation, have initiated widespread vegetation and soil changes in our study area. Most previous studies of floodplain forests have indicated that elevation is the dominant factor structuring plant communities (Dollar et al., 1992; Robertson et al., 2001; Burke et al., 2003); however, in this study, elevation was relegated to the third axis as soil properties were correlated to the first two axes. Furthermore, in relatively undisturbed floodplain systems, baldcypress communities are typically dominant at the lowest elevations (Hupp, 2000; Wilder and Roberts, 2004) but they had the second highest relative elevation of plant communities in this study. Current vegetation and soil communities represent responses to pre- and post-channelization environments, but post-channelization responses suggest a shift in tree species composition to disturbance tolerant species, particularly red maple. These results indicate that channelization has not only altered current plant community composition, but it has also altered the dominant abiotic processes (i.e., hydrology, sediment deposition) that structure these communities. Diameter distribution data suggest that vegetation changes will continue into the near future. Channelization, excessive sedimentation, and valley plugs are common throughout the Coastal Plain reaches of most rivers and/or their tributaries in west Tennessee and northwest Mississippi (Diehl, 2000) and our observations should be broadly applicable to the region.

Soil surveys of Carroll and Madison Counties indicate that sweetgum, cherrybark oak, green ash, and willow oak are typical associates of soils found along the Obion-Forked Deer River system (U.S. Department of Agriculture, 1978, 1984). Timber survey data collected downstream of the study site on the MFFD River lists mixed oak, sweetgum, and baldcypress as the dominant overstory species in the early 1980s (Vandergriff, 1982). These previously common species no longer appear to be influential in the overstory on the study site, nor do they appear to be successfully reproducing in the understory. Instead, red maple is the dominant species on the study site, although flooded areas with flowing water are generally dominated by water tupelo. Wilder (1998) and Wilder and Roberts (2004) found that red maple dominated the subcanopy in floodplain depressions and flats on several west Tennessee rivers that were channelized and had levees. Wilder (1998) attributed the increase in red maple to hydrologic changes associated with channelization and levees.

In the post-channelization environment valley plugs formed in the channelized ditch and forced the river to recapture old meanders along certain sections, valley plugs have expanded upstream changing depositional environments upstream and downstream of the valley plug, and landowners have established levees at various points within the selected reach. As a result, stands appeared to represent a combination of pre- and post-channelization communities, with older trees (‘‘remnant’’ species) representative of pre-channelization hydrology and soil characteristics and younger trees representative of post-channelization hydrology, soil characteristics, and land-use patterns. The pre-channelization or ‘‘remnant’’ component of stands on the MFFD River (age 50+ and generally large diameter) contains species typical of minor river bottoms in west Tennessee, including baldcypress, water tupelo, red maple, and some scattered green ash and mixed oak species. In contrast, the post-channelization component of stands (less than 50 years old and generally small diameter) consists of rapid colonizers (e.g., red maple, box elder, sycamore) suited to multiple soil types and typical of disturbed sites (Hupp, 1992).

Vegetation associations were not directly linked to specific geomorphic features as defined by Happ et al. (1940) as we predicted; however, this may be a result of the abundance of red maple throughout the site, spatial variability in site conditions across some features, and similar life history strategies (i.e., disturbance tolerant) of red maple, black willow, and river birch. Clearly, plant communities were responding to current and past depositional and hydrologic conditions. For example, seven of eight plots dominated by snags were located in a ponded feature (Fig. 1), upstream of one valley plug and downstream of another on the study reach, and fell between the channelized ditch and the old river meander. Valley plug formation within the channelized ditch, sediment influx into the old meander, and beaver activities have resulted in permanent flooding throughout most of the ponded feature. One stand, Stand G (Fig. 4), corresponds with the sand accumulation geomorphic feature (Fig. 1) and contains the highest percentage of sand ($47.6 \pm 9.7\%$) and lowest percentage of clay ($14.2 \pm 2.8\%$) of any stand on the study site. This high sand content is due to the deposition and subsequent splay of sand onto the

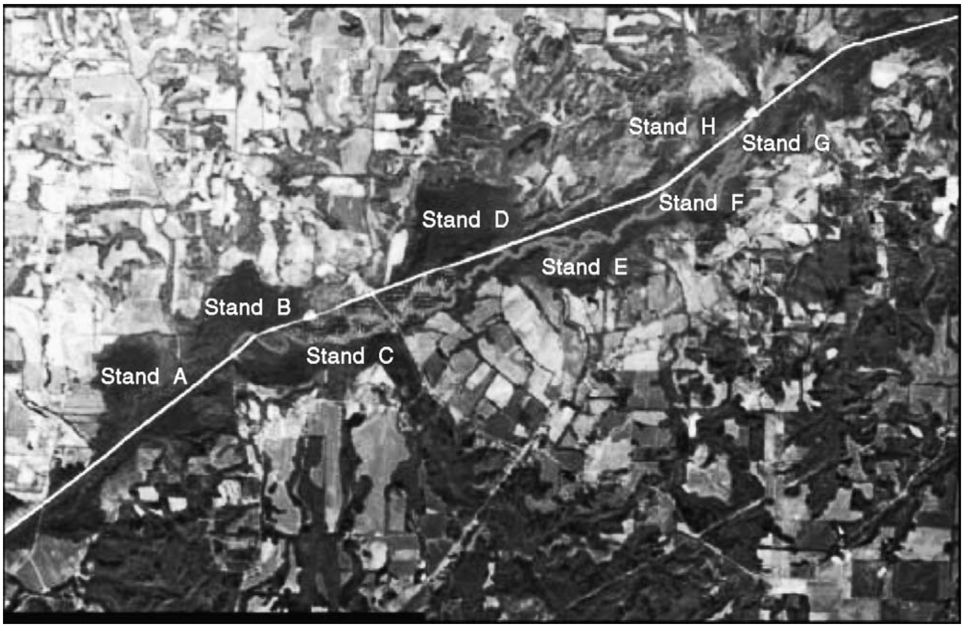

Fig. 4. Map of the Middle Fork Forked Deer River study site, with individual stands identified by letter in order from downstream to upstream.

floodplain as water traveling downstream in the ditched canal encounters the valley plug and splays across the floodplain. Although Stand G supports three vegetation associations (red maple, river birch, and black willow), all three species are indicative of highly disturbed sites and these plots were composed almost entirely of red maple of small diameter classes with a mean age of 19.4 ± 1.63 ($n = 10$) years. This site represents the most recently disturbed site on the study route.

Similarly, relatively high sand content is present in several plots of Stand F (Fig. 4), another sand accumulation feature, and red maple, black willow, and river birch are common associations. However, permanently flooded, flowing channels interspersed across this feature provide ideal habitat for water tupelo. Water tupelo associations are also interspersed in relict and new channels in several geomorphic associations along the study route. Thus, individual plant species are responding to local hydrologic and depositional environments, whereas Happ's (1940) classification provides a broad classification that will have inherently high variability in the hydrologic and depositional environment. In fact, in retrospect, Happ's (1940) description of these features does suggest hydrologic and depositional variability across these features.

Soil communities have also been affected by channelization activities. Organic matter content, percent clay, and magnesium content are all factors related to the flooding regime of particular sites in bottomland hardwood forests (Wharton et al., 1982). Typical alluvial floodplains of the southeastern United States contain high percentages of clay in the swamps (48%) and bottomlands (45%) followed by sand (29–34%) and silt (21–23%) (Wharton et al., 1982). The soils of the MFFD River do not follow this trend. Instead, mean percent silt values were particularly high ($\geq$42.3%), followed by sand and then clay: a reflection of the origin of the MFFD River sediments from the silty loess bluffs and underlying coarse sands.

Soil chemistry patterns and relationships with species associations as defined by our multivariate analyses were related primarily to textural characteristics and site hydrology. For example, CEC varies as a function of soil pH and textural characteristics (Barnes et al., 1998). Differences in the ability of clays, silts, and sands to contribute to the CEC of a soil affect the types and amounts of cations the soil can support. As a result, sandy soils typically have a lower CEC and, therefore, contain fewer nutrients available for plant uptake.

Likewise, Mg typically varies as a function of site hydrology (Messina and Conner, 1998). Magnesium plays an important role in plant photosynthesis and carbohydrate metabolism (Devlin, 1975). Messina and Conner (1998) suggest that the Mg present in thin layers of organic matter overlying mineral soils readily mobilizes during flooding, releasing the nutrient for plant uptake. However, Mg can accumulate to toxic levels in continually flooded environments (Mitch and Gosselink, 2000). In our study, therefore, it is likely that Mg as a primary axis in our ordination is reflective of the current hydrologic environment of the species associations.

The effects of channelization on the Middle Fork Forked Deer River are temporally and spatially complex. In most channelized systems, upstream degradation of the stream channel and banks leads to sediment deposition and aggradation downstream (Schumm et al., 1984; Simon and Hupp, 1987). Streambanks also tend to move through a recovery process that takes about 65 years (Hupp, 1992). In our study, the presence of valley plugs and the continued degradation of upstream tributaries and the mainstem create additional spatial complexity. Thus, generalizations regarding upstream to downstream impacts of channelization do not currently apply in this system.

Hupp (1992) used a six-stage channel evolution model (Simon and Hupp, 1987) to describe channel and streambank recovery following channelization. Although this model was developed from extensive research in west Tennessee streams, the model implicitly assumes that upstream channel degradation attenuates and allows for channel recovery. Valley plugs were not prevalent at the time of model development (C. Hupp, U.S. Geological Survey, pers. commun.), at least partly because of extensive snagging operations practiced during that period by local flood control authorities. Because of the continued input of sediments from upstream sources, recovery of our study reach is arrested within the stages III–V of the Simon and Hupp (1987) model and will remain so until upstream degradation ceases.

Currently, storage of sediment in valley plugs may be preventing the characteristic aggradation of downstream sections that typically follows channelization. However, in time this sediment will be slowly reworked by erosional and depositional processes (Jacobsen and Coleman, 1986). Thus, plant communities that are currently undisturbed or recovering may eventually have to contend with large amounts of coarse-grained sediments that will be reworked into the erosion/deposition network.

Rehabilitation of this system necessitates a long-term, landscape-scale solution that addresses watershed rehabilitation in a spatially and temporally hierarchical manner. Cessation of degradation in upstream reaches will be unsuccessful unless sediment inputs are reduced. However, as sediment supplies are removed or severely restricted, entrenchment of portions of the channel is likely (Costa, 1975; Jacobsen and Coleman, 1986). Activities such as restoring hydrology through meander reconstruction, levee dissolution, and reforesting with hardwood species based on landowner desires can improve ecological conditions, but have a low probability of long-term success unless upstream degradation and tributary sediment contributions are reduced.

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