Journal of Forestry, 2019, 1–11
doi:10.1093/jofore/fvz025
Review Article - forest threats
Received October 17, 2018; Accepted April 3, 2019
Advance Access publication May 8, 2019

OXFORD

Review Article - forest threats

Hydrologic Modifications Challenge Bottomland Hardwood Forest Management

Sammy L. King and Richard F. Keim

Sammy L. King (sking16@lsu.edu)), US Geological Survey, Louisiana Cooperative Fish and Wildlife Research Unit, 124 School of Renewable Natural Resources, LSU AgCenter, Baton Rouge, LA 70803. Richard F. Keim (rkeim@lsu.edu), Louisiana State University Agricultural Center, Baton Rouge, LA 70803.

Abstract

Bottomland hardwoods are floodplain forests along rivers and streams throughout the southeastern United States. The interrelations among hydrology, soils, geomorphic landforms, and tree species composition are the foundation of forest management in bottomland hardwoods, and historically their correspondence has allowed for somewhat predictable forest responses based upon the hydrogeomorphic setting. However, extensive hydrologic and geomorphic modifications in floodplains have disrupted these interrelations and, on many sites, have created novel disturbance regimes resulting in unpredictable forest responses. Reduced or altered timing of surface flooding and groundwater declines are common in the region and have favored increases in stem densities, particularly of species less tolerant of flooding and more tolerant of shade. In these highly modified systems, more process-level understanding of floodplain hydrology, soil moisture dynamics, interspecific tree competition, and regeneration is needed to develop more effective management prescriptions and for forestry to be represented in integrated water-resource management decisions.

Keywords: wetlands, rivers, bottomland hardwoods, floodplain forest, groundwater, agriculture, flood control

Floodplain forests are valued globally for the numerous ecosystem services they provide, including water quality, flood control, wildlife habitat, and timber production (Jenkins et al. 2010, Capon et al. 2013). Many of these services are strongly dependent upon flooding patterns and river-floodplain connectivity because these characteristics affect forest productivity, species composition, movement and forms of sediment and nutrients, and wildlife habitat (Junk et al. 1989, Megonigal et al. 1997, King et al. 2012).

Despite their value, floodplain forests are under severe pressure worldwide because of urban expansion, water management, expansion of agriculture, and climate change (Schneider et al. 2011, Zarfl et al. 2015, Wohl et al. 2017). These pressures are similar to those faced by rivers in general, in which ecosystem services are facing continually increasing demands and where developing effective management techniques require ongoing innovation in the face of increased complexity (Palmer et al. 2009, Schindler et al. 2014).

In the southeastern United States, floodplain forests are referred to as bottomland hardwoods (BLH). The greatest concentration of BLH historically occurred within the Mississippi Alluvial Valley (MAV), but the ecotype also dominates floodplains throughout the Gulf and Atlantic coastal plains (Wharton et al. 1982, McWilliams and Rosson 1990). Historically, there were nearly 25 million ac of BLH in the MAV alone. Frequent flooding limited agriculture there until the 20th century, but extensive flood-control measures and high commodity prices eventually led to the conversion of more than 70 percent to agriculture (National

Management and Policy Implications

Traditional forest-management techniques in bottomland hardwood forests were developed in more recently and less intensely modified floodplains and were dependent upon broad correlations among hydrology, geomorphology, soils, and vegetation. Disruptions in these relations because of hydrologic and geomorphic changes, such as altered timing of river flows, groundwater declines, and channel entrenchment, have rendered some techniques ineffective or unpredictable on many sites. A process-level understanding of hydrology, regeneration, and tree growth is needed to develop more effective forest-management strategies, including timber management and identifying specific water needs for these forests. Projected agricultural intensification and climate uncertainty provide urgency to these research needs.

Research Council 1982). Some converted lands later proved to be unsuited for agriculture, so there has been subsequent afforestation of about 500,000 hectares of marginal farmlands back to BLH, mainly through federal incentive programs, since the late 1980s (King et al. 2006, Mitchell et al. 2016).

These large changes in forest area have received substantial attention (King and Keeland 1999, Stanturf et al. 2000, Twedt et al. 2006, Gordon and Barton 2015), but afforestation alone does not re-establish all important ecosystem functions such as those related to flooding (Hunter et al. 2008, Faulkner et al. 2011). Although there is now more BLH forest land than there was at the peak of agricultural use, hydrological changes because of flood control and other water-management measures that made agriculture possible remain and are affecting forests in pervasive ways that are not well described or understood. Societal demands for ecosystem services from BLH and from water resources are likely to increase in the future, and there are inherent conflicts between these (Schindler et al. 2014). Thus, water-dependent BLH ecosystems represent an important resource where there has been a large financial investment, but for which the future is uncertain.

Despite the obvious importance of flooding in BLH, the details of how flooding and forest functions are linked are not completely understood. As a result, most current floodplain forest-management decisions are based more on historical experience and empirical relations rather than on a functional understanding of how physiological processes govern plant responses to their complex environment. The ongoing intensification of water management has increasingly disrupted the predictability of forest responses to management by changing the hydrological landscape and has substantial implications for BLH on many sites. The objectives of this paper are to: (1) summarize the current state of understanding of how water controls basic BLH forest ecology; (2) outline the nature of hydrologic changes on selected rivers and floodplains in the southeastern United States, with an emphasis on the MAV; (3) apply our current best understanding to broadly describe effects of those hydrological changes on BLH; and (4) assess current management strategies and future research needs in the context of the existing and emerging hydrologic realities.

Hydrologic Control of Bottomland Hardwood Ecology

Floodplains are formed from the erosion and deposition of sediments (Leopold et al. 1964). The patterns and rates of sediment deposition and the characteristics of the sediment itself (e.g., texture) affect the distribution of BLH through effects on drainage, nutrients, flooding, groundwater, and related factors (Hodges 1997). Floodplains often have diverse geomorphic features, including natural levees, backswamps, and flats, that differ in elevation, soil textural class, and hydrologic conditions. Rivers in floodplains meander, so the same point on the landscape may support different geomorphic and hydrologic features through time, and there is complex soil stratigraphy, such as clays overlaying sands, all of which have important implications on groundwater that are not always apparent at the surface (Pöschke et al. 2015).

In minimally modified floodplains, the interrelations among geomorphic features, soils, and hydrology control tree species distributions and form the foundation for BLH forestry (Putnam et al. 1960, Wharton et al. 1982, Hodges 1994). In the face of the bewildering complexity that results, the first generation of BLH management tools tended to simplify these interrelations, using the most obviously relevant characteristic of the site: growing-season flood duration (Bedinger 1971, Hook 1984). Describing the distribution of BLH tree species in terms of flood zones provided a clear and concise concept to guide land-management decisions (Larson et al. 1981). Over time, and with experience, the tree species and stand structures that resulted from various silvicultural practices within each flooding zone became predictably manageable (Putnam et al. 1960). This is essentially the foundation upon which extensive subsequent improvements have been based.

The underpinnings of the relations between species distribution and flooding were, however, understood in terms of gross hydrogeomorphic patterns. Little process-level information was incorporated, nor, with relatively unaltered, or recently altered, hydrology, was it needed. For example, numerous early studies examined absolute flood tolerance of seedlings (e.g., Hosner 1960, Hosner and Boyce 1962), and focus has only recently shifted to the complete suite of processes controlling regeneration and establishment of BLH species (e.g., Streng et al. 1989, Jones et al. 1994, Kroschel et al. 2016) or on competitive interactions among species across the flood gradient (e.g., Allen et al. 2016). Although most species are broadly classifiable in terms of shade and flood tolerance, those classifications provide little predictive power of how species respond to hydrologic change (Battaglia et al. 2004).

There are three water sources for BLH systems: precipitation, groundwater, and river water (Figure 1). The relative dominance of each imparts a distinct range of local variability, yet the contribution of each source varies among watersheds, river reaches, geomorphic features, years, and seasons. Water sources are not always distinct or identifiable because of varying hydrologic connectivity among sources. Hydrologic connectivity is a complex concept in four dimensions: longitudinal (upstream to downstream), lateral (river to floodplain to upland and vice versa), vertical (surface to groundwater and vice versa), and temporal (Ward 1989). Flood frequency, flood duration, soil moisture, groundwater recharge, sediment transport, and, by extension, numerous biological processes of plants and animals are highly dependent upon hydrologic connectivity in floodplains (Ward 1989, King et al. 2012). However, the roles of some water sources such as groundwater—its movement and depth across the floodplain and its interconnections with the river and regional aquifers—remain largely unknown because historically they mainly co-varied with surface flooding or were absorbed into locally calibrated understanding of flooding–forest relations.

Periodic overbank or surface flooding defines BLH systems, and BLH species are adapted to this seasonal flooding via, for example, aerenchyma, delayed leaf out and root production, and hydrochorous seeds (Kozlowski 2002, Burke and Chambers 2003). Similarly, shallow rooting of BLH species is an adaptation to high water tables (Wharton et al. 1982), although strong quantitative data on rooting depths and plasticity in root morphology are scant.

Tree growth, at least for some species, demonstrates some plasticity in growth patterns in relation to water sources. For example, some work has found that tree growth changes when site conditions change: Gee et al. (2015) found that interannual variability of growth of green ash was correlated with river stage prior to a levee isolating the stand from overbank flooding, but then became correlated with rainfall instead after the levee. Similarly, Allen and Keim (2017) found baldcypress growth was more correlated to recent deviation in flooding depth from long-term mean than it was to absolute flooding depth, suggesting that there is morphological plasticity to long-term variations in hydrological growing conditions. However, plasticity and responses to hydrologic change vary by species and site. For example, Palta et al. (2012) found that baldcypress growth increased after flooding was reduced on the Savannah River floodplain, but Gee et al. (2015) found that green ash growth decreased after levee establishment, although wetter sites were less impacted.

Surface flooding is an important agent of tree mortality (Mann et al. 2008) and, thus, disturbance to stands (Allen et al. 2019). In general, flooding can reduce stem density (Hanberry et al. 2012), thereby

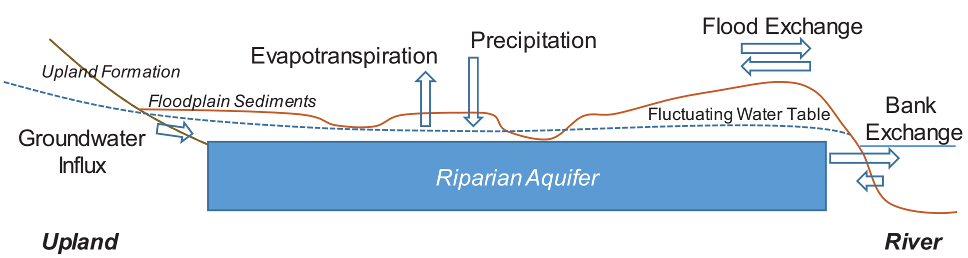

Figure 1. Hydrological budgets for humid-region floodplains. The character of floodplain forests such as southern bottomland hardwoods may depend on a variety of water sources, depending on climate, geology, and position within the floodplain.

affecting stand competition processes. Mortality of mature trees can be relatively rapid and acute with severe hydrologic alterations (e.g., Harms et al. 1980), or slower and punctuated in combination with other disturbances such as wind (e.g., Conner et al. 2014). In addition, flooding disturbance is a strong control on species composition of regeneration because it selects for flood tolerance in physiological terms, but also for phenological differences in seed dispersal and seed germination overlain on timing of flooding (Streng et al. 1989, Kroschel et al. 2016). Given these sensitivities, it is possible that, for example, shifts in timing of flooding with little change in duration of flooding could induce compositional shifts by altering regeneration with little or no impact on overstory mortality. Even if flooding does not cause mortality, its timing affects growth differently by species (Allen et al. 2016), so that shifts in flood timing could also alter competition and shift canopy positions and species composition.

One important relation between flooding and BLH species composition is that there is a general trend that flood-tolerant tree species are often not shade-tolerant and vice versa (Hall and Harcombe 2001, Lin et al. 2004, Battaglia and Sharitz 2006). Regeneration of shade-intolerant species such as oaks (*Quercus* spp.) requires relatively large canopy disturbance so that adequate sunlight is available to seedlings (Meadows and Stanturf 1997). Historically, communities of shade-intolerant species, including red oak in many places, were sustained by river meandering, frequent flooding, ice storms, beaver, and fire. Furthermore, although little studied, canopy gaps created by single tree-fall appear often to be too small to regenerate oaks (King and Antrobus 2001, Oliver et al. 2005). We postulate that flooding disturbance significantly affected the light environment of historic BLH forests through periodic mortality throughout all canopy layers sufficient to allow for oak regeneration. Disturbances such as these may have been similar to silvicultural manipulations found to be successful in regenerating oaks (Gardiner and Hodges 1998, Lockhart et al. 2000).

While flooding has historically structured BLH systems, and considerable research has focused on flood tolerance, drought tolerance of BLH has received scant attention. The effects of drought on seed production and germination, seedling establishment, and tree growth and survival are largely unexplored, although recent drought in Texas and Oklahoma caused substantial BLH overstory mortality (Moore et al. 2016). Drought and flooding may also interact with each other. For example, it is plausible that periods of intense flooding followed by drought can result in acute mortality of trees because of the loss of fine roots during flood episodes (Burke and Chambers 2003, Miao et al. 2009) hampering water uptake during drought (Doffo et al. 2017). Mortality of forest trees and regeneration is generally greater when exposed to multiple stressors (Niinemets 2010), and the addition of drought stress could become more common with increased variability in climate or because of anthropogenic modifications to floodplain hydrologic processes.

Hydrologic Change in Floodplains of the Southeastern United States

As is typical for floodplains, the present floodplain forests of the southeast are a product of disturbance. However, the natural disturbance regime has been shifted by pervasive human alteration. Prior to 1850, clearing of floodplain forests of the southeastern United States by Native Americans and snagging logs from the channels to improve steamboat travel affected forest composition and channel form (Foreman 1928, King et al. 2005, Wohl et al. 2017). At that time, log rafts up to 160 miles in length were common on many southeastern rivers and likely forced water and sediments onto the floodplains at lower discharges than if channels had been clear. Most of the human alterations of this era were to forest structure or local river modifications, and, although clearing of BLH forests for agriculture was common, the large-scale hydrological processes that structured these systems remained mostly intact (King et al. 2005).

Floodplains of the region had the potential to be productive agricultural lands, but frequent and extended flooding (Therrell and Bialecki 2015) limited the rate and extent of conversion to agriculture. Flood-control levees were constructed locally, but their effectiveness and longevity varied widely before the 20th century. Following the catastrophic flood of the Mississippi River in 1927, the US Congress passed the Flood Control Act of 1928 and ushered in the largest and most intensive flood-control project in the world in the MAV. To accomplish the goal, over 3,500 miles of levees were constructed, thousands of miles of streams were channelized (i.e., straightened and steepened to increase flow velocity and drainage efficiency), and hundreds of channel-training structures were placed in rivers (Alexander et al. 2012). The Mississippi River was also shortened by 152 miles by cutting off meanders (Biedenharn and Watson 1997), steepening the gradient and increasing flow velocities. The reduced flooding associated with these flood-control activities facilitated dramatic agricultural expansion through the 1970s. The flood-control projects, agricultural conversion, and recent shifts to irrigated agriculture have subsequently resulted in widespread, pervasive hydrological changes, including severe depletion of some shallow aquifers and reduced streamflow in some rivers through groundwater pumping (Clark et al. 2011, Welch et al. 2011, Coupe et al. 2012, Konikow 2013, Mitra et al. 2016).

Floodplain modifications were not limited to the MAV, nor was agriculture the only impetus for change. Extensive dam systems were placed along many rivers, including the Tennessee and White rivers for flood control and hydropower, and navigation locks and dams were installed along others, including the Arkansas and Red rivers. Virtually all rivers in East Texas now support at least one dam, primarily to provide municipal water supply for large urban centers (Alldredge and Moore 2014, Matthews and Marsh-Matthews 2015, Texas Water Development Board 2017).

These activities have directly and indirectly produced pervasive geomorphic and hydrologic changes throughout floodplains of the southeastern United States (Hupp et al. 2009a). Although specific, long-term hydrologic changes to rivers in the region are difficult to quantify because of the abundance of regional changes and a paucity of hydrologic data prior to modifications, extensive levee construction and widespread flood-control reservoirs have modified almost every aspect of flooding. Levees essentially eliminate surface connectivity between rivers and floodplains, and generally reduce flooding overall. The downstream effects of dams are less obvious, are not restricted to reducing flooding, and vary according to purpose (e.g., flood control, hydropower). Although flood-control dams generally reduce the largest flood events, they may also lead to increased frequency of minor flooding at times outside the historical flooding season when storage reservoirs are being drawn down. For example, dams have decreased peak flows in the spring and increased low flows later in the year for the White River in Arkansas (Gee et al. 2015) and the Roanoke River in North Carolina (Townsend 2001). Sediment starvation by dams increases riverbed erosion and can lead to channel entrenchment, or lowering of the river bed, which can lead to over-steepened banks and subsequent bank collapse and channel widening, and further disconnection of rivers from floodplains (Hupp et al. 2009b, 2015; Figure 2). Floodplain groundwater can decline as aquifers adjust to entrenched river channels (Sophocleous 2002).

Channelization is a severe modification to streams that both straightens and entrenches streams. In addition to bed degradation, bank collapse and channel widening can also migrate upstream of the channelized region into tributaries until a new base level is attained (Galay 1983, Edwards et al. 2016). Reduced upstream flood frequency, increased flood frequency downstream, and reduced flood duration in the entire floodplain can occur following channelization (Shankman and Pugh 1992), but specific effects vary widely (King et al. 2009). Adjustments to channel entrenchment and other channel changes can take decades (Winkley 1977, Hupp 1992).

Modern Bottomland Hardwood Forests in the Context of Modified Floodplains

The long-term effects of hydrologic and geomorphic modifications on BLH are now being realized through changes in species composition in BLH and associated wetlands (Hupp 1992, Townsend 2001, Oswalt and King 2005, Pierce and King 2008, Stallins et al. 2010, Hanberry et al. 2012, Alldredge and Moore 2014, Gee et al. 2014, Jacobsen and Faust 2014). Both the nature of the hydrologic changes and the resultant effects on forests are poorly understood and are active areas of research (Bejarano et al. 2018). Some recent work has provided insight into specific changes. For example, dams on the Apalachicola River have shifted floodplain communities toward drier systems (Stallins et al. 2010), one site in the MAV completely surrounded by levees is shifting away from flood-tolerant species (Gee et al. 2014), and comparisons of forest composition and structure derived from General Land Office surveys in the MAV of Missouri with those of more recent forest inventory and analysis plots indicated that reduced flooding shifted BLH forests to more shade-tolerant and less flood-tolerant species, increased stem densities, and decreased mean diameters (Hanberry et al. 2012).

Altered hydrological conditions and the consequently altered disturbance regime are only one way that disturbance regimes are different in modern BLH compared with historical conditions. There are other disturbances in these forests that may produce similar results in stands, each of which is being managed—either explicitly or implicitly—in BLH today. For example, Oliver et al. (2005) showed that a reduction in the red oak component in BLH forests and

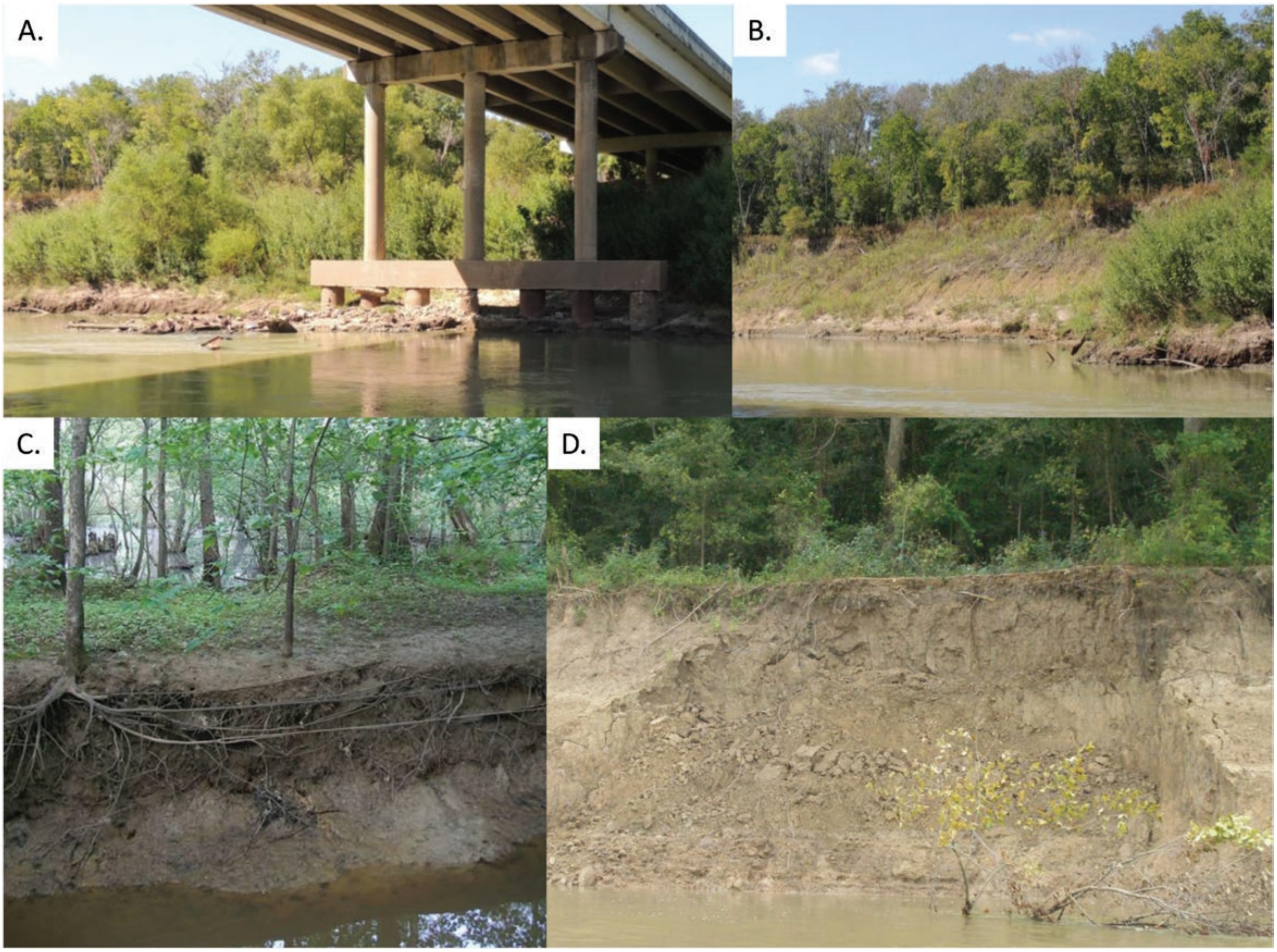

Figure 2. Channel entrenchment from channelization, dams, or other activities can have a wide range of impacts on rivers and associated hydrologic processes on the floodplain. (A) Exposed bridge pilings reveal channel entrenchment (Trinity River, Texas). (B) Following entrenchment, bank height increases and reduces flood frequency and connectivity between rivers and floodplains (Trinity River, Texas). (C) Channelization and entrenchment, channelization, and ditching can result in groundwater draining from the floodplain into the river, lowering groundwater and draining floodplain wetlands. Seepage is visible below the root zone (floodplain of the North Fork Forked Deer River, Tennessee). (D) Over-steepened banks resulting from channel entrenchment can cause bank collapse and channel widening (White River, Arkansas).

an increase in shade-tolerant species were related to timber-management practices that create openings too small for regeneration of red oaks. Although such timber-management practices and other human disturbances can clearly lead to dominance by more shade-tolerant species, larger, fluvial disturbances must have been responsible for historical establishment of red oak stands. We therefore propose that flooding was among the most important historical disturbances leading to establishment and maintenance of many of these stands, and that shifts to shade-tolerant species are consistent with results expected from hydrologic alterations.

Hydrologic alterations may also be affecting forest resiliency. In some areas, precipitation may be becoming the most reliable water source as surface water and groundwater availability have been greatly reduced, possibly making these forests more vulnerable to drought conditions (Moore et al. 2016). Furthermore, if reduced flooding does indeed increase stem densities (Hanberry et al. 2012), drought susceptibility may be further increased: several studies have found drought mortality increases with higher stem densities (D'Amato et al. 2013, Sohn et al. 2016).

The fact that the forests are changing is expected because these systems are disturbance-dependent and associated with rivers that move toward a state of dynamic equilibrium with sediment load, water discharge, and channel geometry (Osterkamp and Hedman 1977). However, the rate of change and the magnitude of hydrogeomorphic alterations mean that many of the rivers, and their associated floodplains, have not reached a new dynamic equilibrium, and further hydrologic adjustment to disturbance is likely to continue. Thus, managers are faced with managing a forest that is responding to hydrologic and geomorphic conditions that are adjusting to both current and past disturbances, many of which occurred off site. Some of these new conditions are within the historic range of disturbance, but in some instances alterations have created novel hydrogeomorphic conditions for these forests that may be outside the disturbance regimes to which they were adapted (Hupp et al. 2009a, Catford et al. 2013, Johnstone et al. 2016). In these instances, there is little basis for predicting and managing stand responses. Furthermore, these changes are evolving temporally and vary spatially in the watershed, so previous forest responses to a given management action may not be a good predictor of future forest responses to the same treatment.

Management and Policy into the Future

A new generation of process-based management is necessary for BLH, in which forestry is explicitly practiced within the physical context of floodplains (Figure 3). Generalized, broad-scale management tools based on correlations among past hydrogeomorphic conditions and vegetation distributions are insufficient on many sites considering the complex and ever-changing hydrogeomorphic conditions of today's floodplains. For example, Meadows and Stanturf (1997) reviewed silvicultural techniques for BLH but did not address hydrologic conditions and their effects on regeneration and stand structure. Their review was consistent with many of the first generation of management tools for these forests, which were developed in floodplains that were far less modified or still adjusting to modifications. Today, as modification continues to intensify, more and more BLH stands are becoming essentially relict stands regenerated under conditions that no longer exist and contain overstory trees that would not regenerate well under current hydrologic conditions. In the face of this rapid change, a greater understanding of the interlinkages among local and watershed-scale hydrogeomorphic processes and species-specific regeneration and competition processes is needed to allow for greater predictive power and thus more refined management techniques.

Adjustments to stand and site assessment and treatment may be needed where hydrologic change is greatest. For example, existing approaches to obtain natural regeneration of oaks, such as clearcutting and patch selection (Meadows and Stanturf 1997), can still be effective but depend on advance regeneration that is lacking or insufficient (K. Ribbeck, Louisiana Department of Wildlife and Fisheries, pers. commun.), so that artificial regeneration may be needed to sustain an oak component (Dey et al. 2012). Hydrologic modification may not be solely or partially responsible for that situation in any given stand, but recognizing that possibility is becoming more important with intensifying modification. Similarly, longstanding tools for site quality assessment are losing applicability

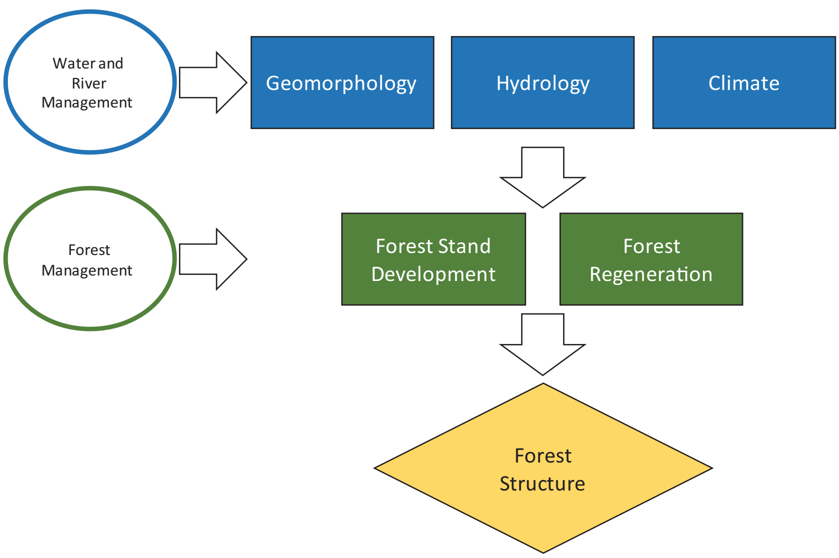

Figure 3. Forest structure and the resultant ecosystem services are the result of forest management with the physical context of floodplains. Management of the physical environment can have a large influence on the same forest processes and attributes manipulated directly by forestry.

in places where hydrologic change is greatest. For example, the site index prediction tool published by Baker and Broadfoot (1979) does not consider the full range of hydrologic conditions that exist in some modern floodplains. New management tools may be needed in the era of intensively managed water and floodplains. For example, a tool to predict regeneration potential that integrates probabilities of the frequency, timing, and duration of floods as they relate to germination times and establishment of the species of interest would be broadly useful for managing regeneration and stand composition. Similarly, tools to assess forest effects of soil moisture dynamics in hydrologically modified systems and their relation to seedling growth and survival are needed, especially in regard to drought.

Local and broad-scale hydrologic restoration could alter stand development processes to promote oak and other desired timber species. Both agriculture and forest management are expected to intensify, and climate uncertainties add to the complexity of the outlook. These increased pressures on floodplains make it likely that water allocation discussions will become widespread in the southeastern United States. To participate in these multiresource plans, forest managers must identify critical hydrologic processes needed to achieve desired outcomes. Although some attention has been given to minimum flows for instream conditions, water needs for existing floodplain forests and associated organisms have largely been ignored. Information on the amount and timing of water needed to sustain tree growth, survival, regeneration, and overall biological diversity is desperately needed to provide a process-level understanding that is currently lacking. Despite the critical importance of water to these forests, there is a general lack of site-specific data available on flooding patterns or groundwater availability. Investing in this critical infrastructure locally can provide data needed to inform the decisionmaking process.

Finally, BLH foresters must strive for hydrogeomorphic literacy. Water drives floodplain ecosystems, and water will arguably be the most contentious natural-resource issue in the coming decades. Water transcends disciplinary boundaries and serves as a connecting point among foresters, fisheries and wildlife biologists, hydrologists, estuarine ecologists, farmers, politicians, and others. Knowing how much water is needed and when it is needed provides a starting-point for critical discussions on water management and allocations that may influence public and private forests as well as instream and estuarine ecosystems and human needs.

Acknowledgments

We thank K. Ribbeck, J. Neal, M.G. Lemon, H. Gee, W. Kroschel, S. Allen, and W. Cochran for critical discussions of ideas in this manuscript. We also thank K. McKnight for a review of the manuscript. Louisiana Department of Wildlife and Fisheries, Texas Parks and Wildlife, and United States Department of Agriculture (USDA) National Institute of Food and Agriculture, LAB94181 (Keim) provided financial support for research studies contributing to this manuscript. Any opinions, findings, conclusions, or recommendations expressed in this publication by R. Keim do not necessarily reflect the view of the USDA.

Literature Cited

Alexander, J.S., R.C. Wilson, and W.R. Green. 2012. A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta. *U.S. Geological Survey Circular* 1375. 43 p. Available online at https://pubs.usgs.gov/circ/1375/C1375.pdf

Alldredge, B., and G. Moore. 2014. Assessment of riparian vegetation sensitivity to river hydrology downstream of a major Texas dam. *River Res. Appl.* 30(2):230–244.

Allen, S.T., and R.F. Keim. 2017. Wetland-tree growth responses to hydrologic variability derived from the development and optimization of a non-linear radial growth model. *Ecol. Modell.* 354:49–61.

Allen, S.T., R.F. Keim, and T.J. Dean. 2019. Contrasting effects of flooding on tree growth and stand density determine aboveground production, in baldcypress forests. *For. Ecol. Manag.* 432:345–355.

Allen, S.T., K.W. Krauss, J.W. Cochran, S.L. King, and R.F. Keim. 2016. Wetland tree transpiration modified by river-floodplain connectivity. *J. Geophys. Res.: Biogeosci.* 121(3):753–766.

Baker, J.B., and W.M. Broadfoot. 1979. *A practical field method of site evaluation for commercially important southern hardwoods*. USDA Forest Service Gen. Tech. Rep. SO-26, Southern Experiment Station, New Orleans, LA. 51 p.

Battaglia, L.L., and R.R. Sharitz. 2006. Responses of floodplain forest species to spatially condensed gradients: A test of the flood-shade tolerance tradeoff hypothesis. *Oecologia* 147:108–118.

Battaglia, L.L., B.S. Collins, and R.R. Sharitz. 2004. Do published tolerance ratings and dispersal factors predict species distributions in bottomland hardwoods? *For. Ecol. Manag.* 198(1–3):15–30.

Bedinger, M.S. 1971. *Forest species as indicators of flooding in the lower White River Valley, Arkansas*. Geological Survey Research 1971, Chapter C. US Geological Survey Professional Paper 750-C.

Bejarano, M.D., C. Nilsson, and F.C. Aguiar. 2018. Riparian plant guilds become simpler and most likely fewer following flow regulation. *J. Appl. Ecol.* 55(1):365–376.

Biedenharn, D.S., and C.C. Watson. 1997. Stage adjustment in the Lower Mississippi River, USA. *Regul. Rivers Res. Manage.* 13(6):517–536.

Burke, M.K., and J.L. Chambers. 2003. Root dynamics in bottomland hardwood forests of the Southeastern United States Coastal Plain. *Plant Soil* 250(1):141–153.

Capon, S.J., L.E. Chambers, R. Mac Nally, R.J. Naiman, P. Davies, N. Marshall, J. Pittock, et al. 2013. Riparian ecosystems in the 21st century: Hotspots for climate change adaptation? *Ecosystems* 16(3):359–381.

Catford, J.A., R.J. Naiman, L.E. Chambers, J. Roberts, M. Douglas, and P. Davies. 2013. Predicting novel riparian ecosystems in a changing climate. *Ecosystems* 16(3):382–400.

Clark, B.R., R.M. Hart, and J.J. Gurdak. 2011. *Groundwater availability of the Mississippi embayment*. US Geological Survey Professional Paper 1785.

Conner, W.H., J.A. Duberstein, J.W. Day Jr., and S. Hutchinson. 2014. Impacts of changing hydrology and hurricanes on forest structure and growth along a flooding/elevation gradient in a South Louisiana forested wetland from 1986 to 2009. *Wetlands* 34(4):803–814.

Coupe, R.H., J.R.B. Barlow, and P.D. Capel. 2012. Complexity of human and ecosystem interactions in an agricultural landscape. *Environ. Dev.* 4:88–104.

D'Amato, A.W., J.B. Bradford, S. Fraver, and B.J. Palik. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecol. Appl.* 23:1735–1742.

Dey, D.C., E.S. Gardiner, C.J. Schweitzer, J.M. Kabrick, and D.F. Jacobs. 2012. Underplanting to sustain future stocking of oak (Quercus) in temperate deciduous forests. *New Forests* 43(5–6):955–978.

Doffo, G.N., S.E. Monteoliva, M.E. Rodriguez, and V.M.C. Luquez. 2017. Physiological responses to alternative flooding and drought stress episodes in two willow (Salix spp.) clones. *Can. J. Forest Res.* 47(2):174–182.

Edwards, B.L., R.F. Keim, E.L. Johnson, C.R. Hupp, S. Marre, and S.L. King. 2016. Geomorphic adjustment to hydrologic modifications along a meandering river: Implications for surface flooding on a floodplain. *Geomorphology* 269:149–159.

Faulkner, S., W. Barrow Jr., B. Keeland, S. Walls, and D. Telesco. 2011. Effects of conservation practices on wetland ecosystem services in the Mississippi Alluvial Valley. *Ecol Appl.* 21(3):S31–S48.

Foreman, G. 1928. Navigation in the early southwest. *Mississippi Valley Hist. Rev.* 15(1):34–55.

Galay, V.J. 1983. Causes of river bed degradation. *Water Resour. Res.* 19:1057–1090.

Gardiner, E.S., and J.D. Hodges. 1998. Growth and biomass distribution of cherrybark oak (Quercus pagoda Raf.) seedlings as influenced by light availability. *For. Ecol. Manag.* 108(1–2):127–134.

Gee, H.K.W., S.L. King, and R.F. Keim. 2014. Tree growth and recruitment in a leveed floodplain forest in the Mississippi River Alluvial Valley, USA. *For. Ecol. Manag.* 334:85–95.

Gee, H.K.W., S.L. King, and R.F. Keim. 2015. Influence of hydrologic modifications on Fraxinus pennsylvanica in the Mississippi River Alluvial Valley, USA. *Can. J. Forest Res.* 45(10):1397–1406.

Gordon, J.S., and A.W. Barton. 2015. Stakeholder attitudes toward reforestation and management of bottomland hardwood forests in the Mississippi Delta. *J. For.* 113(3):308–314.

Hall, R.B.W., and P.A. Harcombe. 2001. Sapling dynamics in a southeastern Texas floodplain forest. *J. Veg. Sci.* 12(3):427–438.

Hanberry, B.B., J.M. Kabrick, H.S. He, and B.J. Palik. 2012. Historical trajectories and restoration strategies for the Mississippi River Alluvial Valley. *For. Ecol. Manag.* 280:103–111.

Harms, W.R., H.T. Schreuder, D.D. Hook, C.L. Brown, and F.W. Shropshire. 1980. The effects of flooding on the swamp forest in Lake Ocklawaha, Florida. *Ecology* 61(6):1412–1421.

Hodges, J.D. 1994. The southern bottomland hardwood region and brown loam bluffs subregion. P. 227–269 in *Regional Silviculture of the United States*. 3rd ed. J.W. Barrett (ed.). John Wiley and Sons, New York.

Hodges, J.D. 1997. Development and ecology of bottomland hardwood sites. *For. Ecol. Manag.* 90(2–3):117–125.

Hook, D.D. 1984. Waterlogging tolerance of lowland tree species of the south. *South J. Appl. For.* 8(3):136–149.

Hosner, J. 1960. Relative tolerance to complete inundation of fourteen bottomland tree species. For. Sci. 6(3):246–251.

Hosner J., and S. Boyce. 1962. Tolerance to water saturated soil of various bottomland hardwoods. *For. Sci.* 8(2):180–186.

Hunter, R.G., S.P. Faulkner, and K.A. Gibson. 2008. The importance of hydrology in restoration of bottomland hardwood wetland functions. *Wetlands* 28(3):605–615.

Hupp, C.R. 1992. Riparian vegetation recovery patterns following stream channelization: A geomorphic perspective. *Ecology* 73(4):1209–1226.

Hupp, C.R., A.R. Pierce, and G.B. Noe. 2009a. Floodplain geomorphic processes and environmental impacts of human alteration along coastal plain rivers, USA. *Wetlands* 29(2):413–429.

Hupp, C.R., E.R. Schenk, J.M. Richter, R.K. Peet, and P.A. Townsend. 2009b. Bank erosion along the dam-regulated lower Roanoke River, North Carolina. P. 97–108 in *Management and restoration of fluvial systems with broad historical changes and human impacts: Geological Society of America Special Paper 451*, James, L.A., S.L. Rathburn, and G.R. Whittecar (eds.). Geological Society of America, Boulder, CO.

Hupp, C.R., E.R. Schenk, D.E. Kroes, D.A. Willard, P.A. Townsend, and R.K. Peet. 2015. Patterns of floodplain sediment deposition along the regulated lower Roanoke River, North Carolina: Annual, decadal, centennial scales. *Geomorphology* 228:666–680.

Jacobson, R., and T. Faust. 2014. Hydrologic connectivity of floodplains, northern Missouri—Implications for management and restoration of floodplain forest communities in disturbed landscapes. *River Res. Appl.* 30(3):269–286.

Jenkins, W.A., B.C. Murray, R.A. Kramer, and S.P. Faulkner. 2010. Valuing ecosystem services from wetlands restoration in the Mississippi Alluvial Valley. *Ecol. Econ.* 69(5):1051–1061.

Johnstone, J.F., C.D. Allen, J.F. Franklin, L.E. Frelich, B.J. Harvey, P.E. Higuera, M.C. Mack, et al. 2016. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* 14(7):369–378.

Jones, R.H., R.R. Sharitz, P.M. Dixon, D.S. Segal, and R.L. Schneider. 1994. Woody plant regeneration in four floodplain forests. *Ecol. Monogr.* 64(3):345–367.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain ecosystems. P. 110–127 in Proceedings of the International Large River Symposium, D.P. Dodge (ed.). Canadian Special Publication Fisheries and Aquatic Sciences 106. Department of Fisheries and Oceans, Ottawa. Available online at http://www.dfo-mpo.gc.ca/Library/111846.pdf

King, K.W., P.C. Smiley Jr., and N.R. Fausey. 2009. Hydrology of channelized and natural headwater streams. *Hydrolog. Sci. J.* 54(5):929–948.

King, S.L., and T.J. Antrobus. 2001. Canopy disturbance patterns in a bottomland hardwood forest in Northeast Arkansas, USA. *Wetlands* 21:543–553.

King, S.L., and B.D. Keeland. 1999. Evaluation of reforestation in the lower Mississippi River Alluvial Valley. *Restor. Ecol.* 7(4):348–359.

King, S.L., D.J. Twedt, and R.R. Wilson. 2006. The role of the wetland reserve program in conservation efforts in the Mississippi River Alluvial Valley. *Wildl. Soc. Bull.* 34(4):914–920.

King, S.L., L.L. Battaglia, C.R. Hupp, R.F. Keim, and B.G. Lockaby. 2012. Floodplain wetlands of the southeastern coastal plain. P. 253–266 in *Wetland habitats of North America: Ecology and conservation concerns*, Batzer, D., and A.H. Baldwin (eds.). University of California Press, Berkeley.

King, S.L., J.P. Shepard, K. Ouchley, J.A. Neal, and K. Ouchley. 2005. Bottomland hardwood forests: Past, present, and future. P. 1–17 in *Ecology and management of bottomland hardwood systems: The state of our understanding*, Fredrickson, L.H., S.L. King, and R.M. Kaminski (eds.). Gaylord Memorial Laboratory Special Publication No. 10, University of Missouri-Columbia, Puxico, MO.

Konikow, L.F. 2013. Groundwater depletion in the United States (1900–2008). US Geological Survey Scientific Investigations Report 2013–5079.

Kozlowski, T.T. 2002. Physiological-ecological impacts of flooding on riparian forest ecosystems. *Wetlands* 22(3):550–561.

Kroschel, W.A., S.L. King, and R.F. Keim. 2016. Tree regeneration in bottomland hardwood forests: A review. *Southeast Nat.* 15(Special Issue 9):42–60.

Larson, J.S., W.S. Bedinger, C.F. Bryan, S. Brown, R.T. Huffman, E.L. Miller, D.G. Rhodes, and B.A. Touchet. 1981. Transition from wetlands to uplands in southeastern bottomland hardwood forests. P. 225–273 in *Wetlands of bottomland hardwood forests. Proceedings of a workshop on bottomland hardwood forest wetlands of the Southeastern United States held at Lake Lanier, Georgia, June 1–5, 1980. Developments in Agricultural and Managed-forest Ecology, vol. 11*, Clark, J.R., and J. Benforado (eds.). Elsevier Scientific, New York.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. *Fluvial processes in geomorphology*. Dover Publications, New York.

Lin, J., P.A. Harcombe, M.R. Fulton, and R.W. Hall. 2004. Sapling growth and survivorship as affected by light and flooding in a river floodplain forest of southeast Texas. *Oecologia* 139:399–407.

Lockhart, B.R., J.D. Hodges, and E.S. Gardiner. 2000. Response of advance cherrybark oak reproduction to midstory removal and shoot clipping. *South. J. Appl. For.* 24(1):45–50.

Mann, L.E., P.A. Harcombe, I.S. Elsik, and R.B.W. Hall. 2008. The trade-off between flood- and shade-tolerance: A mortality episode in Carpinus caroliniana in a floodplain forest, Texas. *J. Veg. Sci.* 19:739–746.

Matthews, W.J., and E. Marsh-Matthews. 2015. Comparison of historical and recent fish distribution patterns in Oklahoma and Western Arkansas. *Copeia* 103(1):170–180.

McWilliams, W.H., and J.F. Rosson Jr. 1990. Composition and vulnerability of bottomland hardwood forests of the Coastal Plain Province in the south-central United States. *For. Ecol. Manag.* 33/34:485–501.

Meadows, J.S., and J.A. Stanturf. 1997. Silvicultural systems for southern bottomland hardwood forests. *For. Ecol. Manag.* 90(2–3):127–140.

Megonigal, J.P., W.H. Conner, S. Kroeger, and R.R. Sharitz. 1997. Aboveground production in southeastern floodplain forests: A test of the subsidy-stress hypothesis. *Ecology* 78(2):370–384.

Miao, S., C.B. Zou, and D.D. Breshears. 2009. Vegetation responses to extreme hydrological events: Sequence matters. *Am. Nat.* 173:113–118.

Mitchell, M., R.R. Wilson, D.J. Twedt, A.E. Mini, and J.D. James. 2016. Object-based forest classification to facilitate landscape-scale conservation in the Mississippi Alluvial Valley. *Remote Sens. Appl. Soc. Environ.* 4:55–60.

Mitra, S., P. Srivastava, and S. Singh. 2016. Effect of irrigation pumpage during drought on karst aquifer systems in highly agricultural watersheds: Example of the Apalachicola-Chattahoochee-Flint river basin, southeastern USA. *Hydrogeol. J.* 24(6):1565–1582.

Moore, G.W., C.B. Edgar, J.G. Vogel, R.A. Washington-Allen, R.G. March, and R. Zehnder. 2016. Tree mortality from an exceptional drought spanning mesic to semiarid ecoregions. *Ecol. Appl.* 26:602–611.

National Research Council. 1982. *Impacts of emerging agricultural trends on fish and wildlife habitat*. National Academy Press, Washington, DC.

Niinemets, U. 2010. Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: Past stress history, stress interactions, tolerance and acclimation. *For. Ecol. Manag.* 260(10):1623–1639.

Oliver, C.D., E.C. Burkhardt, and D.A. Skojac. 2005. The increasing scarcity of red oaks in Mississippi River floodplain forests: Influence of the residual overstory. *For. Ecol. Manag.* 210(1–3):393–414.

Osterkamp W.R., and E.R. Hedman. 1977. Variation of width and discharge for natural high-gradient stream channels. *Water Resour. Res.* 13(2):256–58.

Oswalt, S.N., and S.L. King. 2005. Channelization and floodplain forests: Impacts of accelerated sedimentation and valley plug formation on floodplain forests of the Middle Fork Forked Deer River, Tennessee, USA. *For. Ecol. Manag.* 215(1–3):69–83.

Palta, M.M., T.W. Doyle, C.R. Jackson, J.L. Meyer, and R.R. Sharitz. 2012. Changes in diameter growth of Taxodium distichum in response to flow alterations in the Savannah River. *Wetlands* 32(1):59–71.

Palmer, M.A., D.P. Lettenmaier, N.L. Poff, S.L. Postel, B. Richter, and R. Warner. 2009. Climate change and river ecosystems: Protection and adaptation options. *Environ. Manage.* 44:1053–1068.

Pierce, A.R., and S.L. King. 2008. Spatial dynamics of overbank sedimentation in floodplain systems. *Geomorphology* 100:256–268.

Pöschke, F., J. Lewandowski, and G. Nützmann. 2015. Impacts of alluvial structures on small-scale nutrient heterogeneities in near-surface groundwater. *Ecohydrology* 8(4):682–694.

Putnam, J.A., G.M. Furnival, and J.S. McKnight. 1960. *Management and inventory of southern hardwoods*. USDA Forest Service, Agriculture Handbook No. 181.

Schindler, S., Z. Sebesvari, C. Damm, K. Euller, V. Mauerhofer, A. Schneidergruber, M. Biró, et al. 2014. Multifunctionality of floodplain landscapes: Relating management options to ecosystem services. *Landsc. Ecol.* 29(2):229–244.

Schneider, C., M. Flörke, G. Geerling, H. Duel, M. Grygoruk, and T. Okruszko. 2011. The future of European floodplain wetlands under a changing climate. *J. Water. Clim. Change* 2(2–3):106–122.

Shankman, D., and T.B. Pugh. 1992. Discharge response to channelization of a coastal plain stream. *Wetlands* 12(3):157–162.

Sohn, J.A., S. Saha, and J. Bauhus. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. *For. Ecol. Manag.* 380:261–273.

Sophocleous, M. 2002. Interactions between groundwater and surface water: The state of the science. *Hydrogeol. J.* 10(1):52–67.

Stallins, J.A., M. Nesius, M. Smith, and K. Watson. 2010. Biogeomorphic characterization of floodplain forest change in response to reduced flows along the Apalachicola River, Florida. *River Res. Appl.* 26(3):242–260.

Stanturf, J.A., E.S. Gardiner, P.B. Hamel, M.S. Devall, T.D. Leininger, and M.L. Warren Jr. 2000. Restoring bottomland hardwood ecosystems in the Lower Mississippi Alluvial Valley. *J. For.* 98(8):10–16.

Streng, D.R., J.S. Glitzenstein, and P.A. Harcombe. 1989. Woody seedling dynamics in an east Texas floodplain forest. *Ecol. Monogr.* 59(2):177–204.

Texas Water Development Board. 2017. *2017 State water plan: Water for Texas. Austin, Texas*. Available online at http://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf?d=7918.000000000001; last accessed September 2, 2018.

Therrell, M.D., and M.B. Bialecki. 2015. A multi-century record of spring flooding on the Mississippi River. *J. Hydrol.* 529(2):490–498.

Townsend, P.A. 2001. Relationships between vegetation patterns and hydroperiod on the Roanoke River floodplain, North Carolina. *Plant Ecol.* 156(1):43–58.

Twedt, D.J., W.B. Uihlein III, and A.B. Elliott. 2006. A spatially explicit decision support model for restoration of forest bird habitat. *Conserv. Biol.* 20:100–110.

Ward, J.V. 1989. The four-dimensional nature of lotic ecosystems. *J. N. Am. Benthol. Soc.* 8(1):2–8.

Welch, H.L., C.T. Green, R.A. Rebich, J.R. Barlow, and M.B. Hicks. 2011. Unintended consequences of biofuels production? The effects of large-scale crop conversion on water quality and quantity. US Geological Survey Open File Report 2010-1229.

Wharton, C.H., W.M. Kitchens, E.C. Pendleton, and T.W. Sipe. 1982. *The ecology of bottomland hardwood swamps of the southeast: A community profile*. US Department of Interior, Fish and Wildlife Service, Washington, DC. FWS/OBS-81/37.

Winkley, B.R. 1977. *Man-made cutoffs on the lower Mississippi River—conception, construction, and river response*. Potamology Investigations, Report 300-2. U.S. Army Corps of Engineers Vicksburg District, Vicksburg, MS.

Wohl, E., K.B. Lininger, and J. Baron. 2017. Land before water: The relative temporal sequence of human alteration of freshwater ecosystems of the United States. *Anthropocene* 18:27–46.

Zarfl, C., A.E. Lumsdon, J. Berlekamp, L. Tydecks, and K. Tockner. 2015. A global boom in hydropower dam construction. *Aquat. Sci.* 77(1):161–170.