Land before water: The relative temporal sequence of human alteration of freshwater ecosystems in the conterminous United States

By Ellen Wohl, Katherine B Lininger, and Jill S. Baron

Published in: Anthropocene, vol. 18 , June 2017, p. 27-46

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Abstract

Human alteration of ecosystems prior to Euro-American contact in the area that became the conterminous United States disproportionately affected terrestrial systems compared to freshwater systems, primarily through the use of fire and agriculture in some regions of the United States. After circa 1600 AD, trapping of beaver, along with intensive modification of rivers and wetlands for navigation, mining, flood control, power generation, and agriculture, substantially altered river corridors throughout the country. River corridor here refers to channels of all sizes, from headwater streams to very large rivers, and includes floodplains and wetlands associated with channels. We contend that ecosystem alteration by humans prior to and during Euro-American settlement changed from predominantly terrestrial to both terrestrial and freshwater in a manner that was time-transgressive with Euro-American colonization and U.S. settlement between the 17th and 19th centuries. The extent and intensity of post-Euro-American alteration of freshwater environments in the United States have resulted in widespread river metamorphosis toward more geomorphically and ecologically homogenous systems. Recognition of the rapidity and ubiquity of this alteration, and the consequent instability of many contemporary river corridors, should underpin contemporary river management.

Introduction

At the start of the 21st century, many scientists question whether the cumulative impacts of human use of resources and alteration of ecosystems are exceeding the limits of sustainability for human survival (Rockström et al., 2009; Steffen et al., 2015). Human manipulations clearly exceeded the limits of sustainability for the hundreds of species that have gone extinct within the past five centuries (IUCN, 2007). As rates of extinction have accelerated during the past century, a grim contest has developed among claims for the ecosystems and groups of organisms with the highest rates of extinction. Are the tropical rainforests, with their astonishing biodiversity, experiencing the greatest loss of diversity (Canale et al., 2012), or are amphibians in diverse environments disappearing the most rapidly (McCallum, 2007)? Unfortunately, freshwater fauna in North America are a contender in this contest, with projected future rates of extinction five times greater than the rate for terrestrial fauna (Ricciardi and Rasmussen, 1999). A diverse and complicated history of wetland drainage, river engineering, water pollution, and introduced species underlies high rates of freshwater species extinctions, but it is worth considering when some of the human alterations of freshwater ecosystems began relative to those of terrestrial ecosystems. Here, we review how humans began altering the terrestrial environments of North America prior to the modern imperial and national eras, but discuss how it was only during the intensive industrial development of North America by people of European descent that freshwater environments were substantially altered.

Early explorers and settlers from Europe perceived North America as a wilderness completely unaffected by human activities, a perception that Denevan (1992) referred to as the pristine myth. This perception was tenacious and long-lived, but extensive research has now established that pre-Columbian societies altered at least some portions of terrestrial ecosystems in what is now the United States prior to Euro-American settlement via burning, settlements, and subsistence activities (e.g., Butzer, 1990; Denevan, 1992; Vale, 1998, 2002). Although Native American irrigation techniques physically modified river corridors in certain parts of North America such as the U.S. Southwest (e.g., Doolittle 1992, 2009), we contend that pre-Columbian societies had a much smaller impact on river corridors compared to the terrestrial landscape of North America. In contrast, Euro-American settlement resulted in rapid and significant alterations of both terrestrial landscapes and river corridors in a variety of ways.

This paper reviews existing literature on human alterations of terrestrial and freshwater ecosystems prior to and following settlement of the conterminous United States by people of European descent, with an emphasis on freshwater alterations after Euro-American settlement. Native American here refers to people whose ancestors migrated eastward to North America from Asia and were present in North America prior to Euro-American settlement. Euro-American here describes people who migrated directly from Europe or whose ancestors migrated westward to North America from Europe. We use 1600 AD as a time boundary for considering ecosystem alteration prior to and following Euro-American settlement, although the time of initial direct and indirect contacts between Euro-Americans and Native Americans varied among different regions of the United States and North America. Discussion of the effects of human alteration of freshwater ecosystems focuses on river corridors, which include channels regardless of size, floodplains, and floodplain wetlands, but also briefly reviews lakes. We suggest that understanding the broad patterns of timing in human modifications of terrestrial and freshwater ecosystems provides important insight for managing and protecting these ecosystems.

Human alterations of ecosystems prior to Euro-American settlement

The contention that Native Americans altered terrestrial ecosystems to a greater extent than freshwater ecosystems is based on extensive scholarship focused on diverse geographic regions within the United States, as reviewed briefly in the next two sections.

Alteration of terrestrial ecosystems

Studies of prehistoric societies from various regions of the United States clearly indicate that many Native American communities significantly altered terrestrial ecosystems. Fire was widely used in diverse ecosystems to improve access to animals; improve or eliminate forage for animals on which people depended for food; drive and encircle animals; increase the production of gathered foods; and clear forest vegetation for garden plots or enhance conditions for favored fruit and mast trees (Pyne, 1982; Krech, 1999; Abrams and Nowacki, 2008). Historical sources document these practices from at least some environments in New England (Cronon, 1983; Parshall and Foster, 2002), other portions of the eastern United States (Abrams and Nowacki, 2008), the Cumberland Plateau (Delcourt and Delcourt, 2004), across the prairies (Wohl, 2013b) and some environments within the Intermountain West (e.g., Baker, 2002), to parts of California (Solnit, 1994; Parker, 2002). As Krech (1999) notes in his book on Native American environmental practices, deliberate burning "… may indeed have been the most prevalent tool employed by Indians to manipulate their environment …" (p. 110). The environmental effects of deliberately set fires varied between ecosystems and depended on how frequently and over what extent people used fire, and environmental scientists continue to debate the relative importance of human versus climate controls on fire regimes in diverse areas, as well as local versus regional effects of fire (e.g., Vale, 2002; Marlon et al., 2013; Munoz et al., 2014). Nonetheless, terrestrial ecosystems in much of the United States were at least partly influenced by this form of human-induced disturbance.

Changes to terrestrial ecosystems associated with deliberately set fires included altered type of vegetation cover (e.g., dense forest versus open woodlands or grasslands); altered species composition of plant communities (increased fires favored more fire-tolerant species) and of animal communities associated with those plants; altered carbon and nutrient stocks (Turner, 2010; Buma et al., 2014; McLauchlan et al., 2014); and alterations of water and sediment yield to freshwater ecosystems (Shakesby and Doerr, 2006). The magnitude and spatial extent of all these potential changes in response to deliberately set fires varied as a function of the severity, frequency, and spatial extent of the fires, and much of the ongoing debate about Native American use of fires centers on the details of fire severity, frequency, and spatial extent.

Husbandry of selected herbaceous and woody plants, and deliberate planting and tending of crops, also affected some terrestrial ecosystems. Native Americans grew a variety of crops, but maize formed the central focus of most prehistoric agriculture. Maize was introduced to the southwestern U.S. from Mexico by 2100 BC (Merrill et al., 2009) and spread from there to the eastern United States. Prehistoric people in arid and semiarid regions of the Southwest developed several techniques for growing crops, including seepage fields downslope from springs; water-table fields in wetlands; irrigation ditches such as at Montezuma Wells in

Arizona, USA; mulching to retain moisture; rock-bordered grids to alter the movement of wind and/or water; and low stone terraces known as trincheras on hillslopes (Doolittle, 2000).

Native American agriculture, like Euro-American agriculture, involved replacing native land cover with cultivated plants. Native Americans in the area that became New England used fire to clear patches within the forest, then planted the patches for approximately a decade until soil fertility began to decline. Annual reoccupation of fixed village and planting sites also depleted the supply of firewood in the vicinity and early Euro-American colonists wrote of thousands of acres of treeless land around Native American settlements (Cronon, 1983). Estimated Native American population densities were seven times greater in grain-growing communities in southern New England than in communities in northern New England that relied solely on hunting and gathering (Cronon, 1983).

Pre-contact Native American cultures across large portions of the United States outside of New England and other agricultural areas such as the upper and central Mississippi River valley (Delcourt and Delcourt, 2004) and the Southwest relied primarily on hunting and gathering rather than intensive agriculture, which limited alteration of terrestrial ecosystems. Population density and the intensity of cropping also varied through time within agricultural regions, creating associated fluctuations in the intensity of ecosystem alteration. However, agricultural communities significantly altered at least portions of surrounding terrestrial ecosystems.

The ongoing debate about the spatial extent and intensity of ecosystem alteration by Native Americans prior to Euro-American settlement indicates the difficulty of quantifying prehistoric human effects on terrestrial ecosystems. Generalizing across the conterminous

United States, Native American alterations were less extensive and intensive than subsequent Euro-American alterations because Native Americans had lower population densities, simpler technologies, and lack of integration into global commercial markets and hence lower demands for resources. Consequently, Native American alterations of water and sediment yields from uplands, as well as of plant and animal communities, were for the most part less intense and less persistent than subsequent Euro-American alterations. Native Americans did alter some terrestrial environments, however, in ways that can be detected in geological and archeological records (e.g., Delcourt et al., 1998).

Alteration of freshwater ecosystems

In contrast to the alteration of terrestrial ecosystems through the localized use of fire and planting of crops in diverse regions of the United States, there are few examples of Native American communities significantly altering freshwater ecosystems. People in specific regions depended on fish, mussels, wild rice, and other freshwater organisms for a substantial portion of their nutrition, and at least wild rice appears to have been cultivated to some degree (Doolittle, 2000). There is no evidence, however, that the methods used to obtain these foods substantially altered the morphology of rivers, lakes, or wetlands, or the flow regime of rivers. The Hohokam of central Arizona, one of the most impressive and well-studied prehistoric Southwestern agricultural societies, provide an example of the lack of substantial alteration of freshwater ecosystems.

The Hohokam built the largest canal system in pre-Columbian North America during the 10^{th} to 15^{th} centuries (Doolittle, 1992; Krech, 1999). Scattered villages used a variety of agricultural techniques and at least some of the settlements relied on irrigated agriculture, with crops grown in floodplains using water diverted from rivers. Archeologists disagree on Hohokam population numbers through time. Canal networks built and used during different time intervals make it difficult to infer how much water might have been diverted from the Salt, Gila, Verde, Santa Cruz, and other rivers in the region. However, there is no evidence that the Hohokam diverted enough water to change river processes downstream from their diversion points, and they did not build dams or large water retention structures (Krech, 1999).

Exceptions to the lack of Native American alterations of freshwater ecosystems come from relatively densely populated agricultural societies in the eastern half of the United States. Archeological sites scattered across the eastern United States and the Mississippi Valley indicate that maize-based agriculture helped to support relatively high population densities and more intensive alteration of upland and riparian ecosystems for agriculture. Removal of natural land cover changed water and sediment yields from uplands in a manner recorded in alluvial sediments. Lake and floodplain stratigraphy from some sites along the Illinois and Mississippi Rivers indicates increased sedimentation associated with upland farming during the Archaic Period (8,000-600 BC) and with farming in the valley bottoms of the Mississippi drainage during the Woodland Period (600 BC to AD 1050) (Green and Nolan, 2000). Population density and the style and importance of agriculture relative to hunting and gathering varied through time. Large settlements and intensive agriculture reached an apogee during the Mississippian Period (AD 850-1450), which gave rise to sites such as Cahokia on the Mississippi River near St. Louis. Sedimentation at an archeological site at the confluence of Raymondskill Creek and the Delaware River and at other sites in eastern North America suggests an episode of increased sedimentation in freshwater environments (floodplain, tidal-marsh, lacustrine) during A.D. 1100—1600 in association with maize crops (Stinchcomb et al., 2011). With the exception of river corridors within a few regions of the Mississippi River drainage basin, however, Native American agriculture did not significantly increase sedimentation along river networks across the conterminous United States (James, 2011).

The combined picture that emerges from scattered archeological sites is one of temporal and spatial fluctuations in sedimentation in freshwater ecosystems as population and land use locally increased and decreased over time intervals of centuries to millennia. After circa A.D. 1600, the combined effects of climate change, Euro-American diseases, and Euro-American invasion substantially reduced Native American population levels in the eastern United States and displaced people westward. Relatively densely settled prehistoric communities locally influenced wetlands and riparian areas through farming in riparian areas and increased sedimentation, but, with the exception of the Hohokam, these communities did not develop irrigation networks and there is no evidence that they altered channel morphology or flow regime on the rivers they lived along. Based on the use of fire and upland agriculture by Native American communities in at least some types of terrestrial ecosystems across the United States, and the spatially and temporally limited effects of Native American agriculture on sedimentation in freshwater ecosystems, we generalize Native American alteration of ecosystems as affecting predominantly upland, terrestrial environments.

U.S. rivers circa 1600 AD

Before reviewing Euro-American alteration of freshwater ecosystems in the United States, it is useful to describe the condition of these ecosystems prior to intensive Euro-American settlement of the country and after many centuries of occupation by Native Americans. Most rivers, floodplains, and wetlands throughout the conterminous United States had a substantially different appearance than they do today. First, much more of the landscape was seasonally or perennially inundated (Vileisis, 1997). Diverse wetlands along river corridors and elsewhere – marshes, swamps, lakes, ponds, fens, mires, prairie potholes, playas – were more abundant and larger. Writing of New England as it appeared in 1633, for example, William Wood described swamps 30 to 50 km wide (Cronon, 1983). Spatially extensive black soil layers characteristic of organic matter accumulating in the reducing environment of riverine wetlands inundated by beaver ponds indicate the past location of marshes and swamps, as described for extensive portions of valley bottoms across the eastern and Midwestern United States (e.g., Morgan, 1868; Mills, 1913; Dugmore, 1914). Other historically extensive swamps such as the Black Swamp (~4200 km^2 in extent) along Ohio's Maumee River were likely facilitated by large accumulations of downed wood from trees blown over during tornadoes (Kaatz, 1955). Naturally occurring wood rafts – concentrations of wood extending along many kilometers of river channel and persisting for decades to centuries – blocked the passage of flood waters and created flooded bottomlands along rivers as varied as Louisiana's Red River, the Manistique River of Michigan, Otter Creek in Vermont, Ohio's Maumee River of Ohio, the Guadalupe River of Texas, and the Willamette River of Oregon (Wohl, 2014).

Some of the nation's major aquifers, such as the Ogallala (Basso et al., 2013), had much higher water tables. Many riparian water tables, especially in arid and semiarid regions, were higher (e.g., Stromberg et al., 1996; Falke et al., 2011). Springs and seeps were more common and discharged more water. Floods were unregulated, spilling across extensive bottomlands for weeks to months at a time in environments as diverse as Florida (Douglas, 1947), Illinois (Steele, 1841), the lower Mississippi (Schramm et al., 2009), rivers of the Great Plains fed by snowmelt from the Rockies (Wohl, 2013b), California's Central Valley (Ingram and Malamud-Roam, 2013) and western Oregon and Washington (Sedell and Luchessa, 1981).

Smaller rivers in forested environments in many cases resembled a staircase of ponds created by sequential beaver dams along the channels. From the smallest creeks to the great rivers such as the Ohio, Illinois, Atchafalaya, and lower Mississippi, rivers in forested environments contained abundant wood in the channel and across the floodplain (Wohl, 2014). The earliest written descriptions from channels in New England and the Southeast across the Great Lakes region to the Pacific Northwest emphasize the enormous quantities of individual logs, jams, and enormous wood rafts in rivers. Along with beaver dams on small rivers and floodplains, all of this instream wood slowed the passage of high discharges, forcing water across the floodplain and into secondary channels, as well as into the subsurface to recharge riparian aquifers and help to maintain wetlands. Beaver dams and logjams also facilitated lateral channel migration and formation of secondary channels, which further enhanced the formation of riparian wetlands.

Channels of all sizes were much more physically complex than we are used to seeing today. From prairie creeks and small rivers of the Mid-Atlantic Piedmont that flowed along marshy swales with multiple, subparallel, poorly defined channels (Walter and Merritts, 2008), to large rivers of the Great Plains with braided sections (Williams, 1978; Nadler and Schumm,

1981) and large rivers of the Pacific Northwest with anastomosing planform (Collins et al., 2002), river channels were commonly diffuse and poorly defined. Early explorers, from Louis Hennepin on the Illinois River in 1679 to Mark Twain navigating the Mississippi River during the 1850s (Twain, 1883), and Army engineers on the Willamette River in 1870, complained of the difficulty in following the main course of a river. In arid regions such as central Arizona, channels that are now dry and deeply incised were perennial rivers that supported riparian forests and beaver colonies (Rea, 1983; Webb et al., 2014). Across the United States, river corridors were wetter and more spatially heterogeneous at scales from individual river segments to entire watersheds. This physical diversity equated to abundant and diverse habitat, as well as retention of nutrients and organic matter, and supported an enormous biodiversity (Perry et al., 2002).

Human alterations of ecosystems following Euro-American settlement

Native American cultures followed widely different patterns of settlement that affected their impacts on terrestrial and freshwater ecosystems. Pueblo peoples of the southwestern United States lived in the same dwellings and community locations for centuries, for example, whereas other cultures moved seasonally or at other relatively short time intervals. Individual families of European descent followed the westward-moving frontier of settlement across the conterminous United States over a period of decades. Consequently, exceptions exist to any generalization about settlement patterns of either Native Americans or Euro-Americans. With that caveat, we generalize that settlement of the United States by Euro-Americans commonly involved rapid and more intense alteration of terrestrial environments than terrestrial alterations associated with much of the Native American occupation of the land. Euro-Americans were more likely to settle in communities intended to remain in place for decades to centuries, and Euro-Americans were more likely to rapidly undertake intensive and extensive alteration of land cover for profit (e.g., commercial timber harvest or mining). Land cover change also occurred as a side effect of technological developments, such as substantial increases in fire severity and extent in association with sparks from coal-burning railroad trains (Pyne, 1982).

Contact with Euro-American communities and associated commercial markets also influenced Native American alteration of terrestrial environments by creating competition for existing land and resource uses; altering the geographic extent and population levels of specific Native American groups; and in some cases integrating Native American communities into the enormous commercial markets of Europe and Asia via exports such as furs (e.g., Du Val, 2006; Fenn, 2014; Davidann and Gilbert, 2016). Initial Euro-American contact led Algonquians and Iroquois in the Potomac River basin, for example, to intensify maize production (Rice, 2009). Access to horses greatly increased the mobility of Native Americans of the Great Plains, creating more extensive and locally intensive alteration of grassland ecosystems, especially where Native American access to adjacent mountains was restricted by Euro-American hunting and settlement (West, 1998). Although Euro-American diseases and warfare greatly reduced Native American population numbers across the United States, Native American peoples did not cease to exist with the start of Euro-American settlement. Instead, Native American impacts on terrestrial ecosystems changed, although the details vary between individual Native American groups and through time.

Settlement of the United States by Euro-Americans was also accompanied by many resource uses that affected freshwater environments, most of which occurred nearly simultaneously and were commonly interrelated. These include: beaver trapping; wetland drainage; timber harvest and log floating; placer and lode mining; navigation, river clearing, and channelization; construction of canals; overharvest of freshwater species and fish stocking; construction of dams and water diversions; construction of levees; changes in water and sediment yields from uplands as a result of clearing native vegetation and changing the fire regime; and contamination of surface and ground water via diverse materials ranging from sewage and organic waste to increasingly toxic and persistent synthetic chemicals. The details of which resource use affected freshwater environments in a particular region first and/or most intensively depend on when Euro-Americans first reached the region and the specific characteristics of the region. Commercial timber harvest initiated Euro-American settlement of the northern Great Lakes region, for example, and the modification of channel form and flow regime to facilitate downstream transport of logs constituted the first significant alteration of river corridors in the region. In contrast, agriculture and establishment of towns initiated Euro-American settlement of the eastern seaboard, so that river corridors were first altered through practices such as construction of milldams and drainage of riparian and other wetlands. Figure 1 summarizes these patterns.

The specific effects associated with a particular category of resource use also changed with time as a result of technological changes. Contamination of surface waters by excess sediment, distillery or slaughterhouse waste, or wood waste from sawmills (Kofoid, 1903), for example, later gave way to contamination by synthetic chemicals such as organochlorine pesticides and PCBs (Kraus et al., 2017). Similarly, the size and operation of 18th-century mill dams differed significantly from the size and operation of 20th-century hydroelectric dams.

In the sections that follow we briefly review the diverse human activities that altered freshwater ecosystems during and after Euro-American settlement. Our emphasis is on freshwater ecosystems in order to highlight the contrast between the limited effects on freshwaters by Native Americans and the significant effects on freshwaters by Euro-Americans.

Beaver trapping

One of the earliest Euro-American influences on natural (rather than human) communities in the United States was commercial exploitation of individual species. In many regions of the United States, beaver trapping was the first substantial alteration of river corridors, and beaver populations were decimated prior to permanent Euro-American settlement of an area. Trapping of beavers provides an especially striking example of how Euro-American activities substantially altered freshwater ecosystems.

Ecologists estimate that as many as 400 million beavers (*Castor canadensis*) occupied rivers and wetlands from northern Alaska down into northern Mexico when Euro-Americans first reached North America (Naiman et al., 1988). By building dams, beavers created riparian wetlands that attenuated downstream fluxes of water, fine sediment, organic matter, and nutrients (Naiman et al., 1994; Westbrook et al., 2013; Wegener et al., in press). These effects were recognized by early Euro-American settlers in New England, who prized the fertile soil of valley bottoms formerly occupied by beavers (Cronon, 1983). Beaver-created wetlands supported high diversity of microbes, plants, and animals from insects to mammals (Rosell et al., 2005). Individual beaver meadows – segments of valley bottom with numerous dams and ponds – persisted for thousands of years (Kramer et al., 2012; Polvi and Wohl, 2012) and created resistance and resilience to disturbance within river ecosystems (Hood and Bayley, 2008).

Having driven Euro-American beavers (*Castor fiber*) nearly to extinction by the 12th century in some parts of Eurasia by the end of the 19th century, the Euro-American fur trade systematically and energetically exploited North American beaver populations starting with eastern North America during the early 17th century and progressing westward. North American beaver populations fell to 6-12 million by the mid-19th century (Naiman et al., 1988). Although beaver populations in Eurasia and North America are gradually recovering and beavers are now actively reintroduced as part of river restoration in both continents, scientists are still trying to understand the cumulative effects of severe beaver-population declines on freshwater environments (Hood and Bayley, 2008; Green and Westbrook, 2009; Johnston, 2012; Polvi and Wohl, 2012, 2013). Among the most significant cumulative effects of substantially reduced beaver activity are declines in habitat and biodiversity (e.g., Bartel et al., 2010; Peipoch et al., 2014) and decreased retention of water, solutes, sediment, and particulate organic matter within river corridors (e.g., Wegener et al., in press) (Figure 2).

Wetland drainage

Euro-American immigrants to the United States brought with them a cultural history of wetland drainage. The Dutch were pre-eminent at developing techniques to drain wetlands and Dutch engineers taught the English: by 1649, more than 38,000 ha had been drained in England. George Washington's library included a copy of the 1775 "Practical Treatise on Draining Bogs and Swampy Ground" (Simco et al., 2009). Seventeenth-century Euro-American colonists along the eastern seaboard immediately began altering salt marshes through haying and grazing, as well as draining, diking, and building cities (Baltimore, Philadelphia, Boston, New York, Charleston, and others) on coastal wetlands. Freshwater marshes along rivers such as the Sudbury and Concord in Massachusetts were similarly used for haying as early as the 1630s. These uses of river corridors occurred simultaneously with beaver trapping: more than 10,000 beavers were killed in Connecticut and Massachusetts during the 1620s and more than 80,000 beavers per year were hunted from the Hudson River and western New York during 1630 to 1640 (Vileisis, 1997). The beaver trade ended in New England by 1660 (Cronon, 1983) as the animals largely disappeared from the region as a result of trapping.

Farther south, most colonial governments required landowners to improve their land either through cultivation or by clearing and draining in order to gain land title. By the final decade of the 1700s, almost all rice planters from North Carolina south to Florida had moved their plantations down to tidally influenced freshwater rivers, which they altered with elaborate networks of dikes, check banks, flood gates, ditches, canals, drains, and rice-milling dams. These activities altered the hydrology of river corridors sufficiently to create problems with saltwater intrusions (Silver, 1990; Stewart, 2002). Much of this agriculture was simultaneous with floating of cut timber downstream to sawmills. Loggers altered access to interior timber stands by digging canals and draining portions of extensive wetlands such as the Great Dismal Swamp (late 1760s). In the lower Mississippi River valley, swamp forests along river corridors were logged during initial settlement (1717) for valuable timber from bald cypress, then drained and cropped (Vileisis, 1997).

As Euro-American settlement proceeded westward, riparian wetlands were not necessarily the first target for croplands, but they were commonly modified within two to three decades of settlement. In the Illinois prairie, for example, John Deere's 1837 invention of the self-scouring, steel-bladed plow allowed farmers to cut through the dense network of grassroots and cultivate the uplands following the initial rush of Euro-American settlers at statehood in 1819. The 1850 Swamp Land Act ceded federal swamplands to Illinois and other states with the intention of facilitating wetland drainage using levees, drains, and ditches (Vileisis, 1997) (Figure 3). Alteration of river corridors proceeded rapidly (Wohl, 2013b). In Illinois, state legislation in 1879 facilitated the organization of levee districts that used state funds to build levees, drain wetlands, and channelize rivers (Landwehr and Rhoads, 2003). To cite another example, Euro-American settlement in western Mississippi began about 1830 and by 1840 settlers were channelizing streams and draining wetlands (Shields et al., 1995).

An estimated 89.4 million ha of wetlands existed in the conterminous United States circa 1780 (Dahl, 1990), even though Euro-Americans had been altering river corridors along the eastern seaboard for more than a century. By 1980, wetlands had shrunk to approximately 42.2 million ha. Ten states had lost more than 70 percent of their wetlands by 1980 and 22 states had lost more than 50 percent (Dahl, 1990). In the words of a 1973 Congressional report:

> For the last three-and-a-half centuries Americans have busily settled, developed and cultivated the continent's flood plains. …. In this, they were more bold than prudent…. They stubbornly refused to recognize a flood plain for what it is…. In Delaware, Maryland, and other middle-Atlantic States, extensive drainage networks were dug by

> slaves. Later, in the last decades of the 19th century, drainage districts were established and thousands of miles of trenches gouged to dry up wetlands. (CGO, 1973, p. 2)

The implications of the diverse forms of wetland drainage were twofold. First, wetlands very effectively attenuate downstream fluxes of water, fine sediment, and dissolved and particulate organic matter. By limiting attenuation and storage of these materials, wetland drainage altered riverine flow regimes, sediment transport, and nutrient availability in ways that stressed aquatic, riparian, and coastal biotic communities. Second, wetlands, including those in river valleys, are disproportionately important sources of habitat and food relative to the area that they occupy in the total landscape (Amoros and Bornette, 2002; Dudgeon et al., 2006). Wetland drainage largely eliminated vital wetland habitat for many species of plants and animals.

Timber harvest and log floating

From the eastern seaboard to the Great Lakes and across the Intermountain West and the Pacific Northwest, commercial timber harvest commonly began by using existing waterways to float cut logs to collection booms for transport to sawmills (Wroten, 1956; Sedell et al., 1991; Cowan, 2003; McMahon and Karamanski, 2009). This practice began during the first half of the 17th century in Maine and New Hampshire (Cronon, 1983) and then moved progressively westward with the Euro-Americans. Although railroads subsequently took over the transportation of cut logs during the 19th century, the use of rivers to transport logs typically lasted for at least a decade in regions initially settled by Euro-Americans during the 19th century. In some regions, log transport on rivers persisted much longer as each new area of forest was opened to timber harvest.

Log floating had at least three effects on rivers (Sedell et al., 1991; Cowan, 2003; Wohl, 2014). First, the logs themselves altered channel boundaries, dislodging existing instream wood and battering the channel bed and banks and riparian vegetation, particularly when thousands of logs were floated downstream during a single season (Figure 4). Second, channels were commonly modified to facilitate the movement of logs. Overbank areas such as floodplains and secondary channels were blocked, obstructions within the channel such as wood and large boulders or bedrock were blasted out, and small channels were enlarged. Third, splash dams were built on small to medium channels throughout river networks to facilitate log movement. These small, temporary dams were allowed to fill with water and logs and then dynamited to send the logs rapidly downstream in an outburst flood.

Log floating and associated channel modifications extended from headwater channels just barely wider than the diameter of a log to the largest rivers in the country. Although log floating typically lasted at most a decade in a given region (until all of the marketable timber had been cut or railroads took over transportation of cut logs), the enlargement and simplification of affected channels has persisted for more than a century (Young et al., 1994; Miller, 2010; Ruffing et al., 2015). Removal of upland and riparian forests during timber harvest, where spatially extensive and intensive (i.e., clearcutting rather than selective cutting), also increased water and sediment yields to adjacent river corridors and lakes (Cronon, 1983). As with other land uses affecting river corridors after Euro-American settlement, the timing of timber harvest and log floating varied among regions. New York State led the nation for volume of timber production in 1859, for example, but peak production shifted to states such as Wisconsin and Minnesota during the 1870s to 1900, before shifting to the Pacific Northwest during the early 20th century (Wohl, 2014).

The ecosystem implications of timber harvest and log floating primarily involved loss of habitat abundance and diversity as channels and floodplain wetlands were simplified and laterally disconnected from one another; loss of attenuation of peak flows and storage of nutrients and organic matter as simplified river corridors more rapidly passed material downstream; loss of naturally occurring instream wood and obstructions such as beaver dams that limited longitudinal connectivity and increased lateral and vertical connectivity; and lower biomass and biodiversity of aquatic and riparian organisms as a result of loss of habitat and nutrient retention (Young et al., 1994; Nilsson et al., 2005; Helfield et al., 2007; Ruffing et al., 2015).

Placer and lode mining

Placer deposits are precious metals such as gold that are mixed with alluvial sediments in river valleys and terraces. Lode deposits are in place within bedrock and can occur as veins of precious metals such as gold and silver within igneous or metamorphic rocks, or in the form of ores such as iron or uranium within sedimentary rocks. Placer deposits are inherently associated with freshwater ecosystems and many types of lode deposits are most accessible within river corridors.

By displacing vegetation, soils, and overlying sediments or rock units, both placer and lode mining involved extensive disruption of surface cover and topography, which commonly resulted in substantially increased volumes of sediment entering freshwater ecosystems (Wagener and LaPerriere, 1985; James, 1991, 1994, 1999; Hilmes and Wohl, 1995). Removal of upland forest cover for timber used directly in mining (e.g., timbered ore shafts, fuel for steam-powered stamp mills, charcoal production) and for communities and transportation systems associated with the mining further exacerbated changes in water and sediment yield to freshwater ecosystems (Syvitski et al., 2005), as did construction of water-powered mills. Deforestation commonly occurred extremely rapidly and over large areas in association with mining. A typical furnace associated with iron mining in the eastern and southeastern United States, for example, consumed 0.4 ha of forested land per day while in use (Hart et al., 2008). Increased sediment yields affected river corridors by overwhelming sediment transport capacity and accumulating sediment in channels and on floodplains. Small increases in sediment supply can smother bottom-dwelling organisms or limit the survival of fish (Van Nieuwenhuyse and LaPerriere, 1986; McLeay et al., 1987). Progressively greater amounts of sediment can bury spawning habitat, fill channels and transform them from meandering to braided, fill floodplain wetlands and lakes, and substantially reduce the abundance, diversity, and stability of habitats within the river corridor (Gilvear et al., 1995).

Introduction of contaminants such as mercury used to amalgamate placer gold commonly accompanied mining (Singer et al., 2013), further disrupting freshwater ecosystems with an extremely persistent and highly toxic substance. Mercury, in particular, bioaccumulates within individual organisms and biomagnifies within food webs, limiting the health and survival of a wide variety of organisms (May et al., 2000). Other toxic metals and acids associated with the ores containing precious metals were released into streams and rivers, rendering them virtually barren for kilometers downstream. Acid mine drainage is lethal to fish, invertebrates, and algae. In the Rocky Mountain region alone, more than 15,500 km of streams below mines are impaired and unable to support native freshwater communities (Baron et al., 2002).

Examples of placer and lode mining that directly affected freshwater ecosystems come from iron mining in many portions of the eastern United States during the 18th and 19th centuries (Swank, 1892; Hart et al., 2008); 19th-century placer and lode mining of gold in the Southern Appalachians (Pardee and Park, 1948); and 19th-century placer gold mining in California's Sierra Nevada (James, 1991) (Figure 5) and the Colorado Rockies (Wohl, 2001).

Navigation, river clearing, and channelization

Navigation, river clearing, and channelization here refer to a suite of channel modifications undertaken to facilitate the downstream passage of cut logs to sawmills, reduce overbank flooding, and improve navigation for boats from small flatboats and keelboats to commercial steamboats and barges. Prior to the development of extensive railroads after the Civil War (1861-1865), natural waterways and canals formed the most efficient and economical transport network in the United States for moving large volumes of material. After Robert Fulton designed an efficient steamboat in 1807, rapidly accelerating use of these larger boats required extensive modification of rivers to remove the dangerous snags that could quickly sink a steamboat and to create uniform minimum flow depths through dredging.

It is difficult to over-estimate the extent and intensity of river corridor modification associated with steamboat traffic, which occurred along most rivers of suitable size in the eastern half of the United States during the 19th and early 20th centuries and along a more limited number of rivers in the western U.S. (Wohl, 2014). Desire to enhance steamboat navigation led to: direct modification of channels (removal of millions of logs, dredging, blasting, straightening, blocking off overbank areas); extensive riparian deforestation associated with the need for wood to power the steamboats; greater settlement of remote areas by transporting people and goods to these regions; and federal involvement in river engineering (Harmon et al., 1986; Wohl, 2014). Congressional appropriations for removing wood from rivers date to the very start of the nation, in 1776 (Harmon et al., 1986), but assigning the engineering of inland rivers to enhance steamboat traffic to the U.S. Army Corps of Engineers in 1824 institutionalized these practices (Reuss, 2004).

Some of the most sustained efforts at wood removal included dismantling the enormous, naturally occurring wood rafts such as the famous Great Raft on Louisiana's Red River. While present, this accumulation of wood enhanced overbank flows, channel-floodplain connectivity, and the formation of an anastomosing channel planform in which multiple secondary channels branch around vegetated islands before rejoining the main channel downstream (Triska, 1984; Wohl, 2014). This greatly increased the diversity of aquatic and riparian habitats, as well as retaining dissolved and particulate nutrients, and increasing the extent of biologically rich floodplain wetlands.

Dredging and straightening channels, although undertaken on a small scale by individuals or local groups for more than a century, also accelerated when the U.S. Army Corps of Engineers began channelizing the Mississippi River in the 1870s (Gillette, 1972) (Figure 6). Channelized systems can reduce overbank flooding within the zone of channelization, but commonly exacerbate flooding and sedimentation downstream. Eroding channels can destabilize an entire watershed by dropping base level for tributaries that then incise, further exacerbating downstream sediment yields and typically reducing the abundance, diversity, and stability of instream and riparian habitats in the affected segments of the river corridor (Shields et al., 1995). Even if channelization is not continued, affected channels can require several decades to become stable again (Simon, 1994).

Construction of canals

Prior to development of the national railroad network, bulk materials were most efficiently transported via boats on natural rivers and lakes. Spanning the spatial gaps in this natural freshwater transportation network became a priority of early commercial development in the United States, with private companies and various levels of government contributing to the construction of canals (Cowan, 1997).

The Erie Canal was the first major water project in the United States. Begun in 1817, the canal linked Lake Erie with the Hudson River (Langbein, 1976). A major problem with the 584-km-long canal was seepage of canal water into adjacent soils and rivers crossing the canal, but expected problems of extensive erosion and flooding were not reported. The Erie Canal may have been responsible for the introduction of the nonnative sea lamprey (*Petromyzon marinus*) or alewife (*Alosa pseudoharengus*) to the Great Lakes, where their introduction disrupted lake food webs and caused severe damage to native lake trout and other native fish populations (Christie and Goddard, 2003).

Canals had a relatively short duration as useful transportation networks because of the rapid development of railroads starting in the 1830s (Cowan, 1997). Many of the transportation canals continued to exist for decades, however, creating sources of potential environmental alteration. Other canals were built for different purposes, such as diversion of waste or diversion of water for consumptive uses or for dilution of waste. Canals associated with water diversion for consumptive uses are discussed in a subsequent section of this paper in association with flow regulation. The effects of canals designed primarily for waste disposal are exemplified by the 47-km-long Sanitary and Ship Canal completed in 1900 to link the Illinois River to Lake Michigan. The intent of the canal was to divert wastewater from Chicago into the Illinois River. Prior to construction of the canal, Chicago dumped wastewater into Lake Michigan and extracted drinking water from the lake, leading to repeated outbreaks of cholera (Wohl, 2013b). Diversion of sewage into the Illinois River created a downstream-progressing wave of extinction of freshwater organisms (Richardson, 1918; Colten, 1992). The canal is currently of concern as a corridor for the potential invasion of Asian carp species established in the Mississippi River drainage (Sandiford, 2009). Since the 1800s and end of the 20th century, 180 non-indigenous aquatic species have become established in the Great Lakes (Van Der Zanden et al., 2009). Many of these species were transported via canals. Exotic species have had impacts on virtually every ecological process and niche, causing a cascade of devastation to native fishes and mussels (Mills et al., 1994). The sea lamprey was catastrophic for native lake trout, causing millions of dollars of losses to commercial fisheries. Alewife populations later decimated the lake whitefish commercial fishery. Alewife subsequently became important prey for introduced salmon. White perch migrating up the Erie Canal are now competing with native fishes for food supplies. Since their introduction in the 1980s, zebra mussels and quagga mussels rapidly displaced native unionid mussels (Mills et al., 1994).

The primary environmental alterations associated with canals constructed for diverse purposes are likely to be the stresses that they exert on native freshwater organisms by changing flow regime or providing a pathway for dispersal of pollutants or exotic species. In many cases, these effects persist more than a century after a canal has ceased to serve its intended purpose.

Overharvest of freshwater species and fish stocking

Most of the commercial exploitation of freshwater species that led to precipitous population declines and associated changes in freshwater ecosystems involved either bivalves or fish. Commonly, commercially harvested species were simultaneously impacted by multiple stressors, including overharvest, habitat destruction, pollution, and introduction of exotic species. Examples of species driven nearly to extinction through these processes include Atlantic salmon in rivers of the eastern United States. An estimated 5-12 million Atlantic salmon (*Salmo salar*) spawned in watersheds from the Connecticut River to northern Labrador at the time of Euro-American contact, but these fish had become scarce by the mid-1700s through the combined effects of overfishing, upland clearance and river sedimentation, and mill dams (Montgomery, 2003). Analogous substantial declines occurred during the 18th century in Atlantic sturgeon (*Acipenser oxyrinchus*), shad (*Alosa sapidissma*), alewife (*Alosa pseudoharengus*), and other fish species in the eastern United States as a result of the combined effects of dams that blocked migration routes, overfishing, and sedimentation of river-bed habitat (Walter and Merritts, 2008; Brown et al., 2013). In this context, the ubiquity of dams on nearly every river hosting runs of diadromous fish species is worth highlighting.

Similarly, Pacific salmon and steelhead (*Oncorhynchus* spp.) populations in coastal rivers of the western United States (Lichatowich, 1999) have declined severely as a result of habitat loss, altered connectivity and flow regime caused by dams, overfishing, and nonnative, hatchery-raised fish (Nehlsen et al., 1991).

Unionid mussels in the Mississippi River drainage provide a second example of overharvest. These mussels were harvested for freshwater pearls and for their shells, which were used to culture pearls and to manufacture buttons and other items. Much of the harvest occurred between 1890 and 1930, until mussel populations were severely depleted. Use of the crowfoot, which consisted of multiple, four-pronged hooks attached to an iron bar that was dragged along the streambed, severely disrupted mussel beds and increased bed erosion and water turbidity (Scarpino, 1985). Commercial harvest of at least 50 species of freshwater mussels in many rivers of the United States began in the 1850s and continues today, with the result that many commercial mussel fisheries are now collapsing, leaving mussel populations at dangerously low levels (Anthony and Downing, 2001).

A third example comes from lake sturgeon (*Acipenser fulvescens*) in the Great Lakes, which were abundant prior to the late 1800s and are now estimated to be less than 1% of historic levels as a result of overfishing and other human-induced stressors (DeHaan et al., 2006). Additional examples can be drawn from any commercially exploited fish species in the United States.

Fish stocking has also been widespread in the United States since at least 1871, when Spencer Baird oversaw stocking programs across the nation as head of the US Fish Commission. Fish stocking can involve introduction of species from outside of the United States; introduction of U.S. species to different portions of the country where they do not naturally occur; or introduction of native or nonnative species to fish-less lakes. At least some fish introductions have involved simultaneous attempts to eradicate native species viewed as undesirable, with the most infamous example likely being the 1962 rotenone poisoning of 720 km of the Green River in Utah prior to introduction of game fish for recreational fishing (Wiley, 2008).

One of the most successful examples of nonnative fish stocking involves the introduction of common carp (*Cyprinus carpio*), which were first brought to the United States in 1831, as imports to the State of New York. Baird aggressively promoted carp as a food fish for the farm ponds starting to appear across the eastern and Midwestern U.S. and the fish commission distributed thousands of free carp (Sandiford, 2009).

Introductions of species native to different portions of the country are exemplified by the spread of brook trout (*Salvelinus fontinalis*; native to eastern North America) and rainbow trout (*Oncorhynchus mykiss*; native to cold water, North American tributaries of the Pacific Ocean). Introduction of fish to fishless lakes was typically undertaken to create recreational fisheries in high-elevation mountain lakes (Knapp et al., 2001). Today, 60% of all naturally fishless lakes and 95% of larger deeper lakes in western North America contain nonnative trout (Knapp et al., 2001; Bahls, 1992). Other fish species and freshwater organisms also spread to new habitats through accidental introductions.

Alteration of species present in freshwater ecosystems creates a plethora of effects that ecologists continue to investigate. Among these changes are altered energy subsidies among freshwater, riparian, terrestrial, and marine environments (Cederholm et al., 1999; Baxter et al., 2004). Changes in physical process and water quality can also be associated with the introduced organisms, such as increased turbidity caused by feeding behavior of some types of introduced fish (Zambrano et al., 2001) or changes in lake trophic structure that affect nutrient cycling and water quality (Covich et al., 1999; Schindler and Parker, 2002).

Accidental or deliberate stocking of nonnative freshwater species began with Euro-American settlement of each region of the United States (Halvorson, 2011). The peak period of deliberate stocking of nonnative fish species likely occurred between circa 1870 and 1970, but accidental introductions such as those from ship ballast water continue to substantially impact freshwater ecosystems, as exemplified by zebra mussels from Russia (*Dreissena polymorpha*, introduced circa 1988), several carp species introduced from Asia during the 1970s, and species of algae (e.g., *Didymosphenia geminata*), crayfish (e.g., *Orconectes rusticus*), and other aquatic organisms native to specific regions in the United States but now invading other areas of the country.

Contamination of surface and ground waters

Contamination of surface waters with organic and industrial wastes occurred as soon as Euro-American settlers began commercial exploitation of resources or developed permanent communities. Primary contaminants during the 18th and 19th centuries included human and animal wastes; increased sediment yield from upland soil erosion associated with changes in land cover; and industrial by-products such as sawdust, mercury from placer mining, tannery effluent, or distillery slops (Pisani, 1984; Colten, 1992). Continued development of industry and commercial agriculture during the 20th century dramatically increased the range of contaminants entering surface and ground waters, particularly with rapid advances in the synthesis of organochlorine compounds after circa 1950. National water-quality assessments undertaken during the past two decades indicate ubiquitous contamination of surface and ground waters throughout the conterminous United States (e.g., USGS, 1999; Nowell, 2001; Dubrovsky et al., 2010) as a result of both point sources and non-point sources including atmospheric deposition and terrestrial runoff (Carpenter et al., 1998). Pervasive contamination has resulted in multiple iterations of the Clean Water Act, but the great majority of surface and ground waters in the conterminous United States remain unsafe to drink without treatment. Nutrients from sewage treatment plants, industrial agriculture, and animal feeding operations have caused widespread eutrophication in the United States, leading to substantial loss of biodiversity, increased algal productivity, taste and odor issues, and increasingly harmful algal (cyanobacterial) blooms that are toxic to fish and people. Contamination of surface and ground waters is a primary contributor to the continuing extinction of freshwater species.

Dams and water diversions

Dams were built for diverse purposes following Euro-American settlement of a region, but many of the earliest were mill dams. As Walter and Merritts (2008) documented for the mid-Atlantic Piedmont, tens of thousands of mill dams were built along smaller rivers during the 17th to 19th centuries. The backwater from each dam extended nearly to the base of the next dam upstream as a result of the proliferation of early milling acts that promoted damming for water power. Each of these dams accumulated a 1-5 m thick wedge of sediment in its backwater, effectively burying the small, anabranching channels that existed within extensive vegetated wetlands prior to damming. Sequences of dams affected river process and form for the entire upstream watershed by changing base level.

Mill dams were built within every region of the United States settled by Euro-Americans, primarily with the intent of powering grist mills, saw mills, or early industries. The earliest known commercial dam in the United States is Stockbridge Dam in Massachusetts, built in 1640. Although many of the mill dams were abandoned by the late 19th century, the sediment stored behind each dam still affects river corridors. Merritts et al. (2011) document continuing channel adjustments via processes of bank erosion that release much of the fine sediment and nutrients that create problems in downstream depositional environments such as Chesapeake Bay. Geologists describe these continuing channel adjustments as a transient response to past changes in land cover and rise in base level caused by the presence of mill dams (Merritts et al., 2013), but two or more centuries of adjustment is persistent on human timescales.

In the western United States, Spanish Catholic missionaries built a diversion dam on the San Diego River in California near the end of the 18th century to provide water for irrigating crops (Anonymous, 1916). In portions of the arid and semiarid western United States initially settled by Euro-Americans during the 19th century, water diversions were the first form of freshwater alteration to follow beaver trapping. The South Platte River drainage in Colorado provides an example. Euro-American settlement of the region accelerated dramatically following the 1859 discovery of placer gold. The earliest settlements were mining towns in the mountains and the earliest water diversions were driven by the need to provide water for use in separating precious metals from sediment in placer deposits (Wohl, 2001). Within less than a decade, agricultural settlements were established along the eastern base of the mountain front, and these uniformly relied on surface water diverted from rivers to irrigate crops. By 1876, for example, all of the available surface water had been appropriated in the Poudre River, a tributary of the South Platte, and conflicts were arising from over-appropriation (Wohl, 2001, 2013b).

A similar history of water diversion for mining and agriculture, along with massive increases in sedimentation along river corridors in association with mining, occurred along the western base of the Sierra Nevada in California (James, 1994, 1999). Some diversion structures simply siphon water from a river channel into a pipe or canal. Many forms of diversion, however, rely on water storage via dams within or outside of channels. In river networks simultaneously experiencing multiple human alterations, such as California rivers with mining in the upper basin and irrigated agriculture in the lower basin, dams within channels can store substantial volumes of human-generated sediment and create delays in the downstream movement of this sediment and associated contaminants to depositional environments such as nearshore areas (D. Merritts, pers. comm., March 2017).

Construction of large dams accelerated substantially during the 20th century. By the end of the century, only about 2% of the 5.6 million km of rivers within the United States were unaffected by dams and dams impounded a volume of water approximately equal to the annual continental runoff (Graf, 2001). Among the primary effects of dams large and small on freshwater ecosystems are substantial changes in flow regime; storage of sediment and nutrients; creation of a local base level at the dam and reservoir; loss of migration routes and aquatic and riparian habitat; and changes in water temperature and chemistry and the cycling of carbon, nitrogen, and silica (e.g., Ligon et al., 1995; Nilsson and Berrgren, 2000; Poff and Zimmerman, 2010).

In addition to large dams, hundreds of thousands of stock ponds store water, carbon, and nutrients. These human-created water bodies may have replaced some of the effects of lost beaver-created wetlands. Annual burial rates of organic and inorganic carbon tend to be highest in small, eutrophic lakes and impoundments, for example, and the concentration of organic carbon in sediment is greatest in lakes with a low ratio of watershed to impoundment area (Downing et al., 2008). Small water bodies may thus be disproportionately important with respect to organic carbon storage relative to their size. Severe reductions of beaver populations throughout the United States significantly reduced organic carbon storage in beaver ponds, which have the potential for substantial carbon concentrations in pond sediments and adjacent wet riparian areas (Naiman et al., 1986, 1988; Wohl, 2013a; Johnston, 2014). Small agricultural impoundments have greater sedimentation rates than natural lakes (Downing et al., 2008) and have presumably increased sediment storage of carbon in river networks, but the magnitude of carbon storage in small, natural beaver meadows versus small, agricultural impoundments remains unknown.

Levees

Although the great era of federally built levees occurred during the 20th century, individuals and communities built smaller levee systems much earlier. French and Spanish law that regulated early settlement in the lower Mississippi River region, for example, stipulated that each landowner agree to build a levee to protect claimed land before obtaining legal possession (Reuss, 2004). Levee construction along the Mississippi River at New Orleans began in 1717 (NHRAIC, 1992). Levees were commonly built in association with drainage of riparian wetlands as a means of limiting overbank flows that could inundate those wetlands. Levees were also built to assist in manipulating water levels in deliberately inundated areas, such as rice fields along river corridors. In valley bottoms affected by excess sediment from upstream mining, such as rivers draining California's Sierra Nevada, levees were built to limit overbank flooding exacerbated by sediment deposition that raised channel beds by several meters (e.g., James, 1994). Levee construction in this region accelerated following a major flood in 1862. Continued expansion of levees in regions such as Yuba County, California facilitated urbanization of flood-prone areas that were then inundated by several major floods associated with levee breaks during the 20th and 21st centuries (Montz and Tobin, 2008).

Because systematic records of individual or community levee construction were not kept, it is difficult to estimate the spatial extent and effects of levees built prior to the late 19th century. A massive flood on the Mississippi River in 1858 initiated a national flood-control policy focused on levees and this focus did not change until after the 1927 Mississippi River flood revealed its limitations, although levees continued to be built extensively after 1927. No systematic analysis of the extent of levees appears to exist at present, but many rivers are heavily affected. Along the Mississippi River between St. Louis, Missouri and Head of Passes, Louisiana, for example, federal flood-control levees have reduced floodplain area connected to the channel by 70-90% (Flor et al., 2010).

The ecological effects of levees include severing lateral connectivity between channels and floodplains. Fluxes of water and dissolved and particulate nutrients and organic matter sustain biotic productivity throughout a river corridor, and the ability of organisms to physically move between channels and floodplains is critical to the survival of some species of fish and other aquatic organisms (Junk et al., 1989; Bayley, 1991). By confining peak flows to channels rather than allowing water to spread across the river corridor, levees also increase flow velocity within channels, which can alter habitat and nutrient availability for aquatic organisms (Mattingly et al., 1993).

Changes in water and sediment yields to river corridors

Of all the types of alterations of freshwater ecosystems occurring after Euro-American settlement, change in water and sediment yields to river corridors is the only one present prior to Euro-American settlement, as noted earlier. However, the magnitude of water and sediment entering river corridors increased substantially following Euro-American settlement because of the greater intensity and extent of removal of native upland vegetation. Increased water yields came primarily in the form of greater surface runoff and decreased infiltration, which led to flashier hydrographs, less groundwater recharge, and the drying of springs and ponds (Cronon, 1983). Sediment yields to rivers, lakes, and wetlands typically increased by an order of magnitude following removal of native upland vegetation, a scenario documented repeatedly in the stratigraphy of freshwater environments across the United States (Gottschalk, 1945; Happ, 1945; Knox 1977; Cooper and Brush, 1993; Köster et al., 2007; James, 2011; James and Lecce, 2013; Trimble, 2013).

Increased sediment yields and associated aggradation of channels and floodplains commonly drove additional efforts to engineer river corridors by dredging and straightening channels, for example, in an effort to reduce bottomland flooding exacerbated by loss of channel conveyance (Shields et al., 1995). In the eastern half of the United States, increases in sediment yield were initially driven by upland agriculture and associated removal of native vegetation (e.g., Jackson et al., 2005). In the western half of the country, increased sediment yields initially resulted from mining (Gilbert, 1917; James, 1999) or commercial timber harvest (Whitney, 1994), because agriculture was mostly confined to river corridors or low-lying areas to which surface water could be easily diverted. In either scenario, increased sediment yields typically adversely affected the diversity, abundance, and stability of aquatic and riparian habitat.

U.S. rivers circa 1900 A.D.

The cumulative effects of Euro-American alteration of river corridors can be assessed by considering the characteristics of these environments after one or more centuries of Euro-American occupation. By 1900, river corridors across much of the United States had already been extensively altered. Hundreds of millions of beavers had been killed, thousands of hectares of wetlands had been drained, and millions of logs had been removed from river corridors (Harmon et al., 1986; Wohl, 2014), which had also been physically simplified through diverse forms of direct channel engineering.

The net effect of these activities was twofold: (1) to reduce the extent of riparian wetlands, both directly through draining wetlands and indirectly by removing or reducing the primary processes responsible for creating riparian wetlands, including beaver dams, logjams, lateral channel movements, and high riparian water tables (Triska, 1984; Patrick, 1995; Vileisis, 1997; Wohl, 2014); and (2) to physically simplify and homogenize river corridors. Homogenization resulted from burying original valley bottoms beneath historic sediment within impoundments; straightening and dredging rivers; removing instream obstructions; blocking lateral connectivity to floodplains and secondary channels; and reducing intra- and inter-annual variability in flow through diversions and dams (Poff et al., 2007; Peipoch et al., 2015). Essentially, Euro-Americans did everything they could to make spatially complex and temporally variable natural river corridors more like simple, uniform irrigation canals.

Physical simplification of river corridors tends to increase flow velocity and the peak magnitude of floods if dams are not present (Higgs, 1987). These changes in hydrology and hydraulics cause increased erosion of the channel boundaries and sediment transport. Increased channel erosion can result in further wetland drainage as riparian water tables decline and can also reduce ground water recharge for base flow (Schoof, 1980). Numerous studies indicate that physically simplified and homogenized river corridors have lower biotic integrity in terms of species richness, diversity, and biomass (Groen and Schmulbach, 1978; Scarnecchia, 1988; Rhoads et al., 2003; Moyle and Mount, 2007).

Mountain streams in the Colorado Rockies provide an example of how physical simplification and homogenization alter biotic communities. Historically, abundant logjams and beaver dams created obstructions with backwaters characterized by greater channel cross-sectional area, deeper flow with lower velocity, finer-grained streambed sediment and storage of organic matter, and enhanced overbank flow and formation of secondary channels (Wohl, 2011; Polvi and Wohl, 2013). The spatial heterogeneity associated with logjams and beaver dams facilitates retention of dissolved and particulate nutrients (Day et al., in review), greater abundance and diversity of aquatic habitat, and greater biomass of salmonid fish (Herdrich et al., in review) and aquatic insect predators such as riparian spiders (Venarsky et al., in review). Historical removal of logjams and beaver dams, even where this removal occurred several decades ago, results in contemporary channels with less spatial heterogeneity (Livers and Wohl, 2016) and lower levels of biotic productivity (Herdrich et al., in review; Venarsky et al., in review).

20th century acceleration of human effects on river corridors

The 20th century was a period of intense, federally financed river engineering in the form of dredging and channelization, as well as construction of levees and dams (Reuss, 2004). Nearly every major river within the conterminous United States was extensively affected by these direct modifications by the end of the century (Graf, 2001). Although ground water pumping for irrigated agriculture began during the 1880s and 1890s in drier regions of the United States, drilling of wells into shallow aquifers greatly accelerated during the 20th century. Early wells were less than 30 m deep, but turbine pumps developed during the early 1960s allowed irrigation wells to access much deeper ground water. Simultaneous development of center-pivot irrigation systems substantially expanded the extent of irrigated crop lands. Withdrawal of shallow and deeper ground water resulted in drying of springs and small streams in arid and semiarid regions (Falke et al., 2010).

The 20th century also saw widespread introduction of algae-enhancing nutrients and persistent pollutants in the form of synthetic chemicals such as pesticides into freshwater environments (Wohl, 2004). As population grew and the industrial and commercial agricultural sectors of the U.S. economy accelerated starting in the 1940s, a national sense of alarm over the extent and intensity of alteration of freshwater ecosystems also grew. This resulted in legislation such as the original Clean Water Act in 1972.

In the final decades of the 20th century, concern grew over the potential effects of climate change on river corridors. The specific effects of changing climate vary among different regions of the United States. Systematic records of precipitation and river discharge indicate that some regions such as the Rocky Mountains are growing drier and experiencing earlier melting and a smaller snowpack (Mote et al., 2005; Stewart et al., 2005), whereas other regions such as parts of the northeastern and north-central United States or lower Mississippi Valley are receiving more precipitation (Karl et al., 1996; National Climate Assessment, 2013). Changes in the type, magnitude, frequency, and seasonal timing of precipitation will cascade through freshwater environments, affecting sediment transport, channel morphology and stability, habitat abundance, connectivity, temperature, and nutrient cycling (Covich et al., 1997; Hauer et al., 1997; Rood et al., 2008; Goode et al., 2012; Eby et al., 2014). Combined with other human-induced changes that limit the ability of aquatic organisms to migrate to more suitable habitat, changing climate may prove to be a major stressor of freshwater environments.

21st century movement toward river restoration

The end of the 20th century and the start of the 21st century also saw a major shift in river management toward increased efforts to restore river ecosystems. The pace of dam removals, particularly of small and medium-sized dams, accelerated across the United States. Many of the rivers affected by dam removal have physically stabilized within months to years as sediment stored behind dams is mobilized and redistributed downstream (e.g., O'Connor et al., 2015). Surprisingly, upstream-downstream connectivity for fish and other aquatic organisms is rapidly restored (Pess et al., in press; Torra et al., 2015), although recovery of biotic communities may take longer.

River restoration has become a billion-dollar industry in the United States (Bernhardt et al., 2007). Many restoration projects focus on relatively short lengths of channel (e.g., 1-2 km) and emphasize physical reconfiguration (Bernhardt et al., 2005). The ability of these types of projects to restore river ecosystem function and biotic communities is likely to be limited, especially because the projects are typically not coordinated within a river basin or driven by ecological understanding of river function (Bernhardt and Palmer, 2011). Major, federally financed programs designed to restore connectivity within river basins across much larger spatial and temporal scales, such as those undertaken on Florida's Kissimmee River (Whalen et al., 2002) (Figure 7) or the Colorado River in Grand Canyon (Cross et al., 2011), are more likely to enhance river ecosystem functions.

Water before land vs land before water

To return to the idea proposed at the start of this paper, the body of research summarized in preceding sections illustrates how Native Americans primarily altered limited portions of terrestrial ecosystems across the United States, whereas Euro-Americans rapidly and thoroughly altered both terrestrial and freshwater ecosystems. The timing and magnitude of alteration of terrestrial versus freshwater environments following Euro-American entry into a region depended on the specific resources initially exploited by these immigrants (Figure 1). In some cases, upland resources such as mineral deposits or timber were exploited first, although removal of minerals commonly increased sediment yield to river corridors and cutting of timber typically involved extensive, essentially simultaneous, modification of rivers. In humid climates, agriculture typically began on uplands because bottomlands were saturated for substantial portions of the year. In arid and semiarid climates, Euro-American agriculture typically began in riparian areas and relied on extensive modification of river channels and flow regimes (e.g., Worster, 1985; Wohl, 2001). Even where initial Euro-American activities focused exclusively on uplands, the effects on freshwater environments were commonly rapid and significant because of the lack of any sediment control in regions where native vegetation was removed for mining, timber harvest, grazing, or cropping.

The speed and magnitude of change in sediment yields and responses of river corridors depended primarily on two factors. The first was the spatial extent, intensity, and speed of changes in land cover. The second influential factor was the resistance and resilience of the portion of the landscape and river network under consideration (Webster et al., 1975; Brunsden and Thornes, 1979; Brunsden, 2001). Even in relatively small watersheds of a few hundred square kilometers, headwater portions of the river corridor can respond more rapidly and in different manners than mainstem or downstream portions of the river corridor (e.g., Trimble, 2013).

Quantitatively comparing the magnitude of Native American alterations of terrestrial or freshwater ecosystems to the magnitude of Euro-American alterations is difficult because of limited quantitative data for the initiation and duration, spatial extent, and intensity of alterations associated with each group of people, as well as important differences among geographic regions within the United States. There is no question, however, that all forms of ecosystem alteration increased substantially with Euro-American settlement of the United States. Although many of the alterations associated with Euro-American settlement occurred nearly simultaneously in terrestrial and freshwater ecosystems because of the synergy in resource use between uplands and river corridors (e.g., cutting upland timber and floating cut logs down rivers), we feel justified in making the broad generalization that freshwater ecosystems were minimally altered by human occupation of the United States prior to Euro-American contact. This situation changed dramatically as soon as Euro-American commercial interests created a demand for beaver fur and accelerated once Euro-Americans began to settle in the United States. Consequently, when attempting to evaluate 'water before land' versus 'land before water' in the context of either Euro-American settlement and resource use alone or Euro-American alterations relative to those of Native Americans, the most appropriate formulation varies between diverse geographic regions of the United States. As a whole, however, Euro-Americans altered freshwater ecosystems earlier in their history of occupation of a geographic area and to a greater extent than Native Americans.

The contemporary effects of this extensive Euro-American alteration of freshwater ecosystems across the conterminous United States appear in the form of accelerated extinction of freshwater species (Ricciardi and Rasmussen, 1999); chronic problems with surface-water quality in rivers and lakes (e.g., GAO, 2013); increasing flood damages despite more than a century of focused efforts to reduce flood hazards (Cartwright, 2005); and increasing shortages of water for human consumptive uses (GAO, 2014). Although some of these problems stem partly from other causes (increased flood damages, for example, also reflect increasing population and infrastructure within floodplains (Cartwright, 2005)), they have helped to make river and wetland restoration a commercial market worth well over a billion dollars a year in the United States (Bernhardt et al., 2007). In this context, it is helpful to understand the history of human alterations of freshwater ecosystems and to use this history to gain insight into the form and function of these ecosystems through time.

Today the extent of both terrestrial and freshwater ecosystem modification in the conterminous United States is nearly total, although the alteration took place at different times. Recovery, too, of terrestrial and freshwater systems, is displaced in time and space. Land in the eastern U.S. was cleared for Euro-American agriculture and timber and charcoal production starting in the 1600s and during the period 1820-1880 more than 80% of the land was open (Foster, 1992). Abandonment and reforestation started in 1850 and increased progressively through the early 20th century, approaching complete reforestation circa 1940. Although these second-growth and sometimes third-growth forests differ, in terms of processes such as carbon fluxes and nutrient retention (Turner, 2010), from forests with a history of only natural disturbance, tree regrowth has restored many of the functions provided by pre-settlement forests. Restored functions include changing how precipitation inputs move through and across hillslopes (Jones, 2000); stabilizing hillslopes by intercepting precipitation and increasing soil cohesion through roots (Johnson et al., 2000); and helping to retain organic matter and nutrients in upland environments (McLauchlan et al., 2014).

Recovery of freshwaters, where this has occurred, is only a few decades old at most. The rate of dam removals is increasing (O’Connor et al., 2015) and river and wetland restoration are widely attempted, with varying success (e.g., Wohl et al., 2015b). Rivers can respond rapidly to some restoration actions such as dam removal or restored connectivity (Doyle et al., 2005). However, recent syntheses suggest that many restoration projects are of limited success for at least four reasons. First, the scale of restoration does not begin to match the scale of land use in most watersheds (Bernhardt and Palmer, 2011). Second, the ecological function of rivers remains impaired by well-established invasive species (Yard et al., 2011), persistent contaminants (Bernhardt and Palmer, 2007), and increasingly warmer temperatures. Third, persistent legacy effects of land use may have moved the freshwater ecosystem into a degraded alternative stable state (Heffernan, 2008; Wohl and Beckman, 2014; Livers et al., in review). Fourth, it is typically not feasible to restore primary input variables such as natural flow (Poff et al., 1997), sediment (Wohl et al., 2015a), or wood regimes (Wohl, 2017). In the absence of dynamic input regimes, river ecosystems are unlikely to fully recover physical complexity that can support ecosystem functions present prior to Euro-American settlement.

Schumm (1969) introduced the phrase *river metamorphosis* to describe a complete and typically rapid alteration of river form and function in response to human activities such as flow regulation. Schumm referred specifically to rivers of the Great Plains, which transformed from wide, shallow, braided channels with minimal woody riparian vegetation to relatively narrow, deep, meandering channels with extensive riparian forests as a result of diversions that reduced peak flows and increased base flows. Analogous metamorphoses occurred in wide, shallow, diffuse channels of marshy regions such as the Everglades (Wohl, 2004) or the mid-Atlantic Piedmont (Walter and Merritts, 2008), where channel engineering and dams created more confined, channelized flows. Brierley et al. (2005), contrasting human alteration of rivers in the Old and New Worlds, proposed that removal of riparian vegetation and instream large wood following Euro-American settlement of the New World rapidly reduced the buffering capacity of riverscapes and effectively lowered the thresholds governing channel stability, such that rivers became highly sensitive to change. Writing primarily of rivers in Australia, Brierley et al. (2005, p. 41) noted that “The short lag time between disturbance and metamorphosis, typically measured in terms of a few decades [during Euro-American settlement], ensured that once critical trigger events were experienced it was exceedingly difficult for systems to recover.” Our personal observations of rivers in the conterminous United States and the written and photographic records of these rivers during the past two centuries support this interpretation. As a result of rapid, thorough, and extensive changes in inputs (water, sediment, large wood, nutrients, contaminants), physical configuration, and biotic communities during Euro-American settlement, river corridors cannot fully or completely return to being physically and biologically diverse ecosystems that are resistant and resilient to various disturbances. Recognition of this relatively recent, fundamental, and ubiquitous alteration of river corridors and river ecosystem functions during the past two centuries should underlie river management in the United States.

One of the most important considerations in the context of river management is reflected in the observation of Brierley et al. (2005) that rapid change in variables controlling river form and process creates continuing instability and limits resilience to change. River corridors experience natural, abrupt disturbances such as floods, droughts, or wildfires. Individual portions of a river network can have greater or lesser resistance to these disturbances and exhibit differing degrees of resilience in recovering from the disturbance (Townsend et al., 1997; McCluney et al., 2014). The rapid, widespread, and continuing disturbances created by Euro-American alterations of uplands and river corridors since 1600 have reduced resistance and resilience of rivers throughout the United States, thus increasing the vulnerability of freshwater ecosystems to ongoing changes such as warming climate. Recognition of the ubiquity of changes in river corridors is also critical. There are almost no naturally functioning river corridors remaining in the conterminous United States (e.g., Graf, 2001), which highlights the vital importance of protecting those that do remain.

Acknowledgments

This paper benefited from insightful review comments by Ruth Alexander, Allan James, and Dorothy Merritts.

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