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Review

Impacts on ecosystems, corrective restoration practices, and prospects for recovery: nine case studies in the continental United States

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Abstract. Ecological restoration in the United States is growing in terms of the number, size, and diversity of projects. Such efforts are intended to ameliorate past environmental damage and to restore functioning ecosystems that deliver desired levels of ecosystem services. In nine current restoration case studies from across the continental United States, this paper details (1) the impacts of the original disturbance and compounding secondary issues that compel restoration, (2) the corrective practices applied to advance restoration goals, and (3) the prospects for recovery of ecosystem services, including those involving associated animal populations. Ecosystem-altering impacts include flood control (Kissimmee River), flood control and navigation (Atchafalaya Basin), damming for irrigation-water storage (Colorado River) and hydroelectric power (Elwha River), logging and fire suppression (longleaf pine forest), plant invasions that decrease fire-return intervals (Great Basin shrublands, Mojave Desert), nutrient and sediment loading of watersheds (Chesapeake Bay, Mississippi River delta), and conversion of natural lands to agriculture (tallgrass prairie). Animal species targeted for recovery include the greater sage-grouse (Great Basin shrublands), the red-cockaded woodpecker (longleaf pine forest), the south-western willow flycatcher (Colorado River and its tributaries), the desert tortoise (Mojave Desert), eight salmonid fish (Elwha River), and the blue crab and eastern oyster (Chesapeake Bay).

Additional keywords: arid rangelands, exotic species, fire ecology, grassland ecosystems, open forest, riparian ecology.

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Introduction

Current restoration projects throughout the United States are aimed at reversing environmental degradation due to a multiplicity of causal agents, for example, compromised plant and animal populations; invasions of problematic weeds; intentional alterations in land use, hydrologic regime, or fire regime; and nutrient loading of watercourses by upstream agricultural activities. These restoration efforts are driven by a desire to rejuvenate charismatic wildlife species populations, to restore impaired ecosystem services, or to alleviate damage to soil or water resources. Nine major restoration efforts in United States ecosystems impacted by the above issues were chosen as case studies to represent the diversity of impacted ecosystems, causal agents of degradation, ecological modifications, and impacted ecosystem services (Table 1).

These nine restoration efforts are all large in scale, but they vary markedly in geographic extent (Fig. 1) as well as by ecosystem group and by degree of humidity/aridity. They range from the Elwha River restoration (Duda *et al*. 2008), the smallest in extent, to restoration of the tallgrass prairie (Rowe 2010) and institution of sustainable agricultural practices in the Corn Belt (Mitsch and Day 2006; McLellan *et al*. 2015; Arnason 2017), with watershed impacts reaching from the north-central states all the way down the Mississippi River and its tributaries to the Gulf of Mexico (McConnaughey 2017). The longleaf pine forest and tallgrass prairie have been reduced to small remnants of their original extent, mostly by agricultural expansion (Smith 1990; Van Lear *et al*. 2005; Mitchell *et al*. 2006; Kush and Varner 2009). The sagebrush shrublands and the Mojave Desert remain large, but their iconic floras have been greatly diminished by altered fire regimes due to the expansion of flammable invasive annual grasses (Salo 2004; Davies *et al*. 2011).

Perhaps more important than their diversity or size is the significance of the nine restoration case studies. Each was chosen because it is highly significant within the context of recent activities of ecological restoration in the continental (48 states, not including Alaska and Hawai'i) United States. For example, the longleaf pine ecosystem is considered by many to be the most endangered ecosystem in the United States (Kush and Varner 2009). Restoration efforts in the sagebrush shrublands are significant because of large-scale collaboration across several states, motivated in part by the hope of precluding listing of the western sage-grouse as a threatened species (Dumroese *et al*.

Table 1. Nine major restoration efforts (case studies) organised by three ecosystem groups (terrestrial, riparian, and watershed) in order of most humid to most arid within each ecosystem group

Ecosystem	Causal agents of degradation	Modifications	Impacted ecosystem services
Terrestrial			
1. Longleaf pine forest	Fire suppression Altered land use	Reduced fire frequency Canopy fires	Loss of flagship species
2. Great Basin shrublands	Cheatgrass invasion	Increased fire frequency	Loss of sage-grouse habitat
3. Mojave Desert	Altered land use Red brome invasion	Increased fire frequency	Loss of fire-intolerant plant species Negative effect on desert tortoise
Riparian			
4. Elwha River	Damming for power generation	Increased temperature Reduced O_2 content Loss of gravel spawning beds	Decline of salmonid fishery
5. Kissimmee River	River channelling Impoundment	Loss of adjacent wetlands Increased biological O_2 demand	Decline of fishery Algal blooms downstream
6. Colorado River	Damming for irrigation Tamarisk invasion	Altered hydrologic regime Loss of native trees	Status of willow flycatcher ssp.
Watershed			
7. Atchafalaya Basin	Levee construction Channel dredging Oil/gas extraction	Loss of sedimentation Proliferation of Chinese tallow	Land subsidence/saltwater intrusion Loss of wetlands Increased vulnerability to hurricanes
8. Chesapeake Bay	Unsustainable farming practices	Nutrient loading Sedimentation Diminished water clarity *Phragmites* invasion	Eelgrass decline Decline of fisheries
9. Tallgrass prairie/Corn Belt/Gulf of Mexico	Conversion of marginal lands to row cropping Excessive tillage Biofuel policy	Nutrient loading Loss of N in tile drainage water Dead zone in Gulf of Mexico	Reduced water quality Loss of soil fertility Reduced Carbon sequestration Decline of fisheries

2016). Restoration in the Mojave Desert, the most arid part of the United States, faces the challenge of extremely long natural recovery rates (Lovich and Bainbridge 1999). The Elwha River restoration is significant because it is demonstrating what can be done following the largest dam removal in history (Foley *et al*. 2017), as well as for being the first dam removal for the benefit of a fishery (Winter and Crain 2008). Remarkably, restoration of the meandering Kissimmee River in Florida was authorised only 5 years after its channelisation into the C-38 canal was completed in 1971 (Koebel 1995), with restoration costs approaching one billion US dollars (Koebel and Bousquin 2014). Restoration in the Colorado River drainage is notable because of the controversy surrounding tamarisk, which has divided the public into (1) a group that believes this tree has no place in restoration because it is non-native and (2) a group that believes its presence is justified as habitat for an endangered bird (Lamberton 2012). Restoration in the Atchafalaya Basin is significant because it is an excellent story of balancing a variety of commercial and non-commercial interests (Yeoman 2010*b*), as well as the record amount of money that is available for restoration from mitigation funds for oil and gas operations (Day *et al*. 2007) and the Deepwater Horizon oil spill (Marshall 2015). Finally, restoration efforts impacting both Chesapeake Bay and the Gulf of Mexico are significant because they are showing how incentives can prompt a multiplicity of landowners to participate in cleaning up their watersheds for downstream benefit (Snider 2016; Bjorhus 2017). Here, these efforts are presented as case studies organised within three ecosystem groups, namely terrestrial, riparian, and watershed, with three representatives for each. Within each group, the representative case studies are discussed in order from most humid to most arid.

Terrestrial ecosystems

(1) The longleaf pine forest of the humid South-east

At the time of European settlement, longleaf pine (*Pinus palustris* Mill.) dominated 30 million hectares and was present in mixed stands on another 7 million hectares in the south-eastern USA (Van Lear *et al*. 2005). Most of these lands fell within the Coastal Plain region, stretching from Virginia to Texas. Today this ecosystem, noted for its high level of understorey plant species diversity and endemism, is among the most endangered in the United States, occupying less than 5% of its original extent (Mitchell *et al*. 2006; Kush and Varner 2009). Urbanisation, fire exclusion, and conversion to agriculture and plantations of two faster-growing and less fire-tolerant timber species, loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Engelm.), have all compromised the longleaf pine ecosystem (Van Lear *et al*. 2005).

Longleaf pine is a highly fire-dependent species (Kush and Varner 2009), and its maintenance requires frequent low-intensity fires ignited by either lightning strike or human activity. Native Americans and later white settlers instituted a frequent low-intensity fire regime to reduce fuels in order to maintain their settlements and facilitate hunting (Van Lear *et al*. 2005). However, as fire exclusion became accepted practice in the 20th century, a new fire regime of infrequent high-intensity burns was favoured, increasing longleaf pine mortality (Van Lear *et al*.

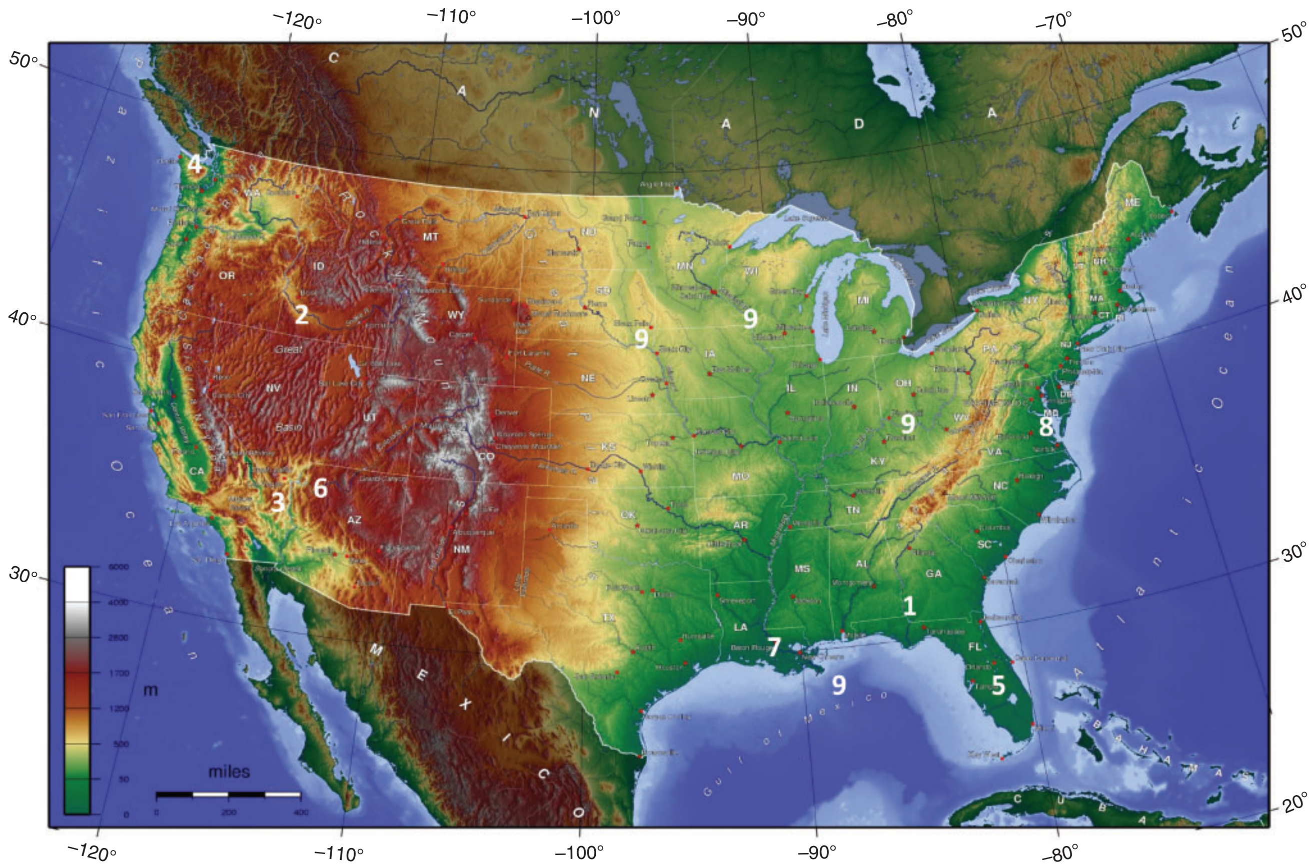

Fig. 1. Locations of nine large restoration efforts in the continental United States: (1) the longleaf pine forest of the humid South-east, (2) the cold-desert shrublands of the Great Basin, (3) the Mojave Desert of the arid South-west, (4) the Elwha River of the humid Olympic Peninsula of Washington, (5) Florida's Kissimmee River, (6) the Colorado River and its tributaries in Arizona, (7) the wetlands of the Atachafalaya Basin of Louisiana, (8) the Chesapeake Bay and its watershed in the mid-Atlantic states, and (9) the tallgrass prairie of the Midwest, its Corn Belt replacement, and the impacted Gulf of Mexico downstream.

2005). A fire interval of 1–3 years is desirable (Mitchell *et al*. 2006), and longleaf forest ecosystems that have not burned in 10 years are considered to be at risk (Kush and Varner 2009).

Fire is required to generate the bare mineral soil needed for longleaf pine seeds to germinate and establish (Kush and Varner 2009), and associated understorey plant species require sunlight penetration through an open canopy (Van Lear *et al*. 2005). An understorey of wiregrass (*Aristida stricta* Michx., *A. beyrichiana* Trin. & Rupr.) is needed to fuel the desired frequent low-intensity fires, and restoration practitioners have learned how to manage forests for wiregrass seed production with prescribed early summer burns (Seamon 1998). But when longleaf pine stands do not burn in a timely fashion, hardwood species, particularly oaks (*Quercus* spp.), invade and draped litter may accumulate in the mid-story, increasing the risk of a canopy fire (Kush and Varner 2009). Broadleaf litter is less flammable than that of longleaf pine and wiregrass, thus the absence of fire generates a positive feedback response that drives the replacement of pine with oak (Mitchell *et al*. 2006).

In 1985 a restoration program was implemented by The Nature Conservancy at the Appalachicola Bluffs and Ravines Preserve in the Florida panhandle (Seamon 1998). This site had a history of logging, fire suppression, feral hog foraging, planting of slash pine, and hardwood expansion. Restoration involved prescribed burns, planting of containerised longleaf pine seedlings, and reintroduction of wiregrass. Prescribed fire began in the Flomaton Natural Area in Escambia County, Alabama in 1995 (Kush and Varner 2009). To overcome a heavy fuel load, four low-intensity burns were prescribed over a 7-year period. Although Flomaton was one of only five remaining virgin longleaf pine forests, it was clear-cut in 2008 to restore a diverse understorey.

The Bugaboo Scrub Fire of 2007 (Fig. 2) burned over half a million acres in Georgia and Florida from 16 April until its containment on 22 June (Bugaboo Scrub Fire 2017). Two interstate highways, I-10 and I-75, were closed for days due to poor visibility caused by smoke. High winds from Tropical Storm Andrea exacerbated the fire, but it was eventually extinguished by the heavy rains of Tropical Storm Barry. In Florida's nearby Osceola National Forest, 'accelerated restoration' treatments have been applied since the fire to thin longleaf pine, chop saw palmetto (*Serenoa repens* [W. Bartram] Small) shrubs, burn or mulch the chopped material, and replant longleaf pine seedlings (Ray *et al*. 2017). Restoration objectives were to achieve an overstorey of mature pine forest with multiple age classes, maintain a mid-story with no hardwoods present, regenerate an

Fig. 2. The 2007 Bugaboo Fire in Florida pine forest, United States. Image courtesy of Wikimedia (public domain). https://upload.wikimedia.org/wikipedia/commons/2/23/Bugaboo_forest_fire.jpg

intact native understorey, and restore healthy populations of native wildlife.

Longleaf pine forests provide habitat for the red-cockaded woodpecker (*Leuconotopicus borealis*), an endangered keystone species that produces tree cavities in older living longleaf pine trees, thereby providing habitat for two dozen other animal species (Mitchell *et al*. 2006). This bird has been successfully relocated to uninhabited or under-inhabited habitat, including artificial cavities (Van Lear *et al*. 2005). Gopher tortoises (*Gopherus polyphemus*), another keystone species, are abundant in frequently burned longleaf pine forest (Mitchell *et al*. 2006), and their burrows and dens support over 300 species of vertebrates and invertebrates (Van Lear *et al*. 2005). However, tortoises and their associated species are lost under closed canopies (Mitchell *et al*. 2006).

(2) The cold-desert shrublands of the Great Basin

Big sagebrush (*Artemisia tridentata* Nutt.; BSB) communities are compromised by altered fire regimes, both through piñon pine (*Pinus edulis* Engelm., *P. monophylla* Torr. & Frém.) and juniper (*J. californicus* Carr., *J. grandis* R. P. Adams, *J. occidentalis* Hook., *Juniperus osteosperma* [Torr.] Little) encroachment at higher elevations (reduced fire frequency) and invasive annual grasses at lower elevations (increased fire frequency). However, the latter problem is more pernicious (Davies *et al*. 2011). Cheatgrass (*Bromus tectorum* L.), an invasive annual, dramatically alters soil structure and chemistry, and a positive feedback exacerbates the propensity for cheatgrass dominance over time (Jones *et al*. 2015; Appendix B). Wyoming BSB (*A. tridentata* subsp. *wyomingensis* [Beetle & Young] S. L. Welsh) is the subspecies of BSB most desired for restoration efforts, in part because the sites it occupies lack both resistance and resilience to cheatgrass invasion (Chambers *et al*. 2014*b*). Susceptibility to cheatgrass invasion is greater for the sagebrush semi-desert than for the sagebrush steppe, a less arid region (Chambers *et al*. 2014*a*). Invasion may be limited by individual bunchgrasses and soil biocrusts, whose presence minimises gap size and connectivity among gaps (Reisner *et al*. 2013). Care should be taken that these biological components are not compromised by livestock grazing.

Much of the Great Basin is prone to wildfire, primarily due to the cheatgrass problem. In August 2015, the Soda Fire burned 280000 acres in south-western Idaho and south-eastern Oregon over a 2-week period (Bureau of Land Management 2016). The Soda Fire was intense and burned rapidly due to high temperatures and sustained winds. This was the first large-scale fire whose rehabilitation was guided by Secretarial Order 3336, issued in 2015. This order was designed to protect sagebrush habitat by controlling the spread of annual invasives and concomitant wildfires (Dumroese *et al*. 2016). Under this Order, a 5-year response plan has been implemented for the Soda Fire that permits the use of impazapic herbicide on 27 000 acres to control annual weedy grass germination, authorises the building of 25 miles of fuel breaks, particularly near urban areas, and facilitates extensive monitoring and adaptive management. The plan was formulated by a partnership that encompasses five federal agencies plus state agencies in Idaho and Oregon. Once the fire was controlled, helicopters were used to gather 279 wild horses over 9 days. These animals plus others that were bait-trapped over the winter were provided veterinary care and groomed for adoption or return to the land.

Nearly all of the land burned by the Soda Fire had served as habitat for the greater sage-grouse (GSG) (*Centrocercus urophasianus*). The possibility of listing the GSG as a threatened species was a primary consideration in planning restoration seedings subsequent to the Soda Fire (Bureau of Land Management 2016). For example, antelope bitterbrush (*Purshia tridentata* [Pursh] DC) and BSB seed were drilled on 17 500 acres in late autumn, whereas an additional 60 500 acres inaccessible to seeding equipment were aerially seeded in January 2016. In addition, over 1.4 million BSB seedlings were transplanted, many in the vicinity of GSG leks, areas where males gather to exhibit courtship display behaviour to compete for females (Fig. 3).

In the past, restoration seeding efforts in the sagebrush shrublands have emphasised grasses, and more recently native grasses, but currently much greater emphasis is being placed on BSB and native forbs than has been the case previously (Kilkenny and Edwards 2016). Consequently, efforts to develop plant materials of these species are being expanded. These species are being emphasised not only to increase the biodiversity of seedings, but also to address dietary needs of the GSG. The GSG's winter diet consists entirely of leaves and buds of BSB and related *Artemisia* species (Bureau of Land Management 2004), but a diversity of forb species is required in the summer (Dumroese *et al*. 2015). Sage-grouse lack a gizzard, thus they are not granivores and must rely on soft foods (Bureau of Land Management 2004). Chicks are fed a diet high in high-protein insects for the first few weeks of life (Dumroese *et al*. 2015). Native and introduced forbs of the Cichorieae tribe of Asteraceae produce sap with a milky latex that attracts these insects, and seed sources of these species are desired for restoration seedings (Dumroese *et al*. 2016).

Fig. 3. Male greater sage-grouse. Image courtesy of United States Geological Survey (public domain). https://www.google.com/search?q=sage-grouse±images±usgsandtbm=ischandtbo=uandsource=univandsa=Xandved=0ahUKEwjcspT89PDVAhUjslQKHWYHBZoQ7AkIMgandbiw=1280andbih=666#imgrc=kLu7sAwFEBI2HM:andspf=1503613555589

Seeding Wyoming BSB on a broad scale has been attempted for many years, yet success has been limited. Nevertheless, much has been learned, and there is reason to hope that future seedings will be more successful. In many cases, basin big sagebrush (*A. tridentata* subsp. *tridentata*) has been inadvertently seeded in place of the preferred Wyoming BSB, but now seed of these subspecies may be correctly distinguished based on the latter's higher seed mass (Richardson *et al*. 2015). To remain viable, seed must be high in purity and stored under cold and dry conditions (Karrfalt and Shaw 2013). For best results, it should be applied to the soil surface, either on the ground or aerially, during January and must be covered with snow (Meyer and Warren 2015). Competitive weed seedlings may limit BSB establishment, so seeding the winter following a fire, when weed densities are reduced, increases the probability of success (Meyer and Warren 2015). For the same reason, seeding in conjunction with perennial grass species that have competitive seedlings should be avoided (Meyer and Warren 2015).

The effort to support GSG populations has been the largest such effort in United States history, which explains the 2015 decision by the United States Fish & Wildlife Service to refrain from listing this species, at least until the issue is revisited in 2020 (Dumroese *et al*. 2016). The decline of GSG is largely a result of the loss and degradation of habitat (Wirth and Pyke 2003). Most remaining habitat occupies the more northern, higher, or wetter portions of the bird's original range (Dumroese *et al*. 2015). Height, density, cover, and patchiness of BSB are more important determinants of GSG use than subspecies (Bureau of Land Management 2004).

Restoration efforts at higher elevations are addressing threats to the sagebrush shrublands posed by conifer invasion. Since a policy of fire suppression for property protection has been implemented in Owyhee County in south-western Idaho, density of western juniper (*Juniperus occidentalis* Hook.) has increased 3–5-fold relative to historic norms, thereby reducing critical sagebrush habitat for GSG (Stuebner 2017). The GSG avoids areas near western juniper because these trees provide perches for ravens that predate on GSG eggs (Stuebner 2017). The Bureau of Land Management (BLM) is advancing a plan to eliminate junipers that interfere with 70 occupied GSG leks using chain saws and masticators across 940 square miles in Owyhee County (Stuebner 2017). Although this approach may be effective on a small scale, the BLM plans to implement prescribed burning to control juniper on a broader scale (Stuebner 2017).

(3) The Mojave Desert of the arid South-west

The Mojave Desert encompasses parts of southern Nevada and California and adjacent portions of Arizona and Utah. It is the driest and one of the warmest regions of the United States and has suffered from a variety of environmental abuses and neglect. These include recreational off-road vehicle use, a past history of overgrazing and mining, diversion of water resources to irrigated agriculture, urbanisation, construction of roads and utility corridors, air pollution from distant urban centres, particularly Los Angeles, and concentrated military activity (Lovich and Bainbridge 1999). Such stresses have led to the proliferation of exotic plants, increased anthropogenic fire, soil compaction, destruction of soil biocrusts, and erosion. Compacted soils reduce infiltration and moisture-holding capacity, opportunities for plant establishment are infrequent, and restoration costs are high with a low probability of success.

The Mojave Desert is currently threatened by the expansion of exotic, invasive, annual grass species, particularly red brome (*Bromus rubens* L.) (Salo 2004). Red brome has invaded undisturbed lands in the region and increased fuels, leading to increased fire frequency and the loss of native succulent and woody plants (Salo 2004). Fire in the Mojave has traditionally been infrequent due to the inability of sparse patchy vegetation to carry a fire (Lovich and Bainbridge 1999). Mid-elevation shrublands in the eastern and north-eastern portions of the Mojave have so far been most greatly impacted by red brome, as its additional biomass bridges interspaces and pushes fuel loads above a critical fire threshold, leading to the destruction of fire-intolerant species such as creosotebush (*Larrea tridentata* [DC] Coville), Joshua tree (*Yucca brevifolia* Engelm.), and blackbrush (*Coleogyne ramosissima* Torr.) (Brooks and Matchett 2006) (Fig. 4).

Red brome appears to compete directly with native annuals (Brooks 2000), of which there are as many as 250 species, with 80–90 being endemic (Turner 1982). Unlike most of the dormant-seeded, annual native species, red brome germinates early and uniformly without maintaining a seed bank (Salo 2004). Annual natives generally require 20 mm of precipitation to germinate, whereas red brome requires only 10 mm (Salo 2004). Consecutive years of high precipitation stimulate the spread of red brome, whereas consecutive dry winters result in a population crash and retreat to favourable microsites, suggesting an opportunity for control (Salo 2004).

Due to extreme temperatures, high winds, limited precipitation, and low soil fertility, natural recovery may require on the order of a few thousand years (Lovich and Bainbridge 1999).

Fig. 4. Joshua tree woodland with red brome in the understorey at Lost Horse Valley, Joshua Tree National Park, in California, United States. Image courtesy of National Park Service (public domain). https://www.flickr.com/photos/joshuatreenp/22896496603/in/album-72157640982117014/

Revegetation efforts are also limited by weed competition, frequent fire, and compacted soils. Consequently, preservation of remaining undamaged areas should be paramount (Lovich and Bainbridge 1999). Abella *et al*. (2012) found that establishment of an early successional forb community, and particularly desert globemallow (*Sphaeralcea ambigua* A. Gray), best conferred resistance to red brome invasion under both ambient and enriched levels of soil nitrogen (N). Due to the severe environment, direct seedings of native species have had little success, though nursery-reared transplants have fared better when protected from herbivores and supplied with supplemental water (Lovich and Bainbridge 1999). Six years after transplanting, Abella (2017) reported good cover of six shrub species (sweetbush [*Bebbia juncea* (Benth.) Greene], brittlebush [*Encelia farinosa* A. Gray ex Torr.], cheesebush [*Ambrosia salsola* (Torr. & A. Gray) Strother & B.G. Baldwin], white bursage [*Ambrosia dumosa* (A. Gray) W.W. Payne], buckwheat [*Eriogonum fasciculatum* Benth.], and creosote bush [*Larrea tridentata* (DC) Colville]), as well as a forb, desert globemallow, when transplants were watered with 2 mm of water per week for the initial 18-month post-plant period. However, three grass and two other forb species fared poorly.

The Mojave population of desert tortoise (*Gopherus agassizii*) is listed as threatened. Steel energy towers in the desert facilitate predation by providing perches for native ravens (Lovich and Bainbridge 1999). Fires also contribute to tortoise mortality, and Esque *et al*. (2003) estimated that 11% of individuals on one particular fire site were killed. However, tortoise extirpation is unlikely due to their preferred subterranean habitat during summer, when fires are most frequent (Esque *et al*. 2003). Yet losses of this magnitude are devastating to a species that does not reach reproductive maturity for 15–20 years and lives to be 50–80 years old (Esque *et al*. 2003).

Riparian ecosystems

(4) The Elwha River of the Olympic Peninsula of Washington

The removal of two dams to restore the salmon fishery of the Elwha River of Washington's Olympic Peninsula is the largest dam removal project of its kind to date (Duda *et al*. 2011) and the first implemented primarily to benefit a fisheries resource (Winter and Crain 2008). The two privately owned dams were purchased by the federal government for decommissioning and demolition under the auspices of the *Elwha River Ecosystem and Fisheries Restoration Act of 1992* (Elwha Dam 2016). The Elwha Dam was constructed in 1910–12 and rebuilt to a height of 33 m in 1913 due to faulty original construction, forming Lake Aldwell (Duda *et al*. 2008; Elwha Dam 2016). Eight miles further upstream, the Glines Canyon Dam was built to a height of 64 m in 1925–27, forming Lake Mills (Duda *et al*. 2008). These two dams provided hydroelectric power for the Olympic Power Co. to power a pulp mill in Port Angeles, a town located near the point where the Elwha River flows north into the Strait of Juan de Fuca (National Park Service 2017*b*). The Olympic Peninsula encompasses the wettest portion of the United States and is home to a temperate rain forest in Olympic National Park. The Elwha River watershed features the steepest precipitation gradient on the peninsula, ranging from 5500 mm of annual precipitation in the upper basin to 1000 mm at the river's mouth (Duda *et al*. 2008).

Sediment delivery was dramatically reduced by the dams, leading to net erosion of riverbed, including loss of gravelly spawning habitat and delta at the river's mouth (Elwha Dam 2016). Fish ladders were not installed on either dam, leaving only the lower five miles of habitat for anadromous fish (National Park Service 2017*b*). The Elwha River had been home to 10 anadromous runs, including all five species of Pacific salmon (coho [*Oncorhynchus kistuch*], pink [*O. gorbuscha*], chum [*O. keta*], sockeye [*O. nerka*], and Chinook [*O. tshawytscha*]), as well as cutthroat [*O. clarkia*], bull [*Salvelinus confluentus*], and steelhead [*O. mykiss*] trout (National Park Service 2017*b*). Pink and chum salmon posted the greatest declines, and the pink was believed to have been extirpated until they were spotted in the late 1990s (Winter and Crain 2008). Though anadromous fish could not pass Elwha Dam, resident populations of the threatened bull trout and rainbow trout remained above the dam (Duda *et al*. 2011). Remaining runs were largely sustained by hatchery production (Duda *et al*. 2008). The dams disrupted natural fluctuations in river flow and increased temperatures in Lakes Aldwell and Mills from 0°C to 16°C (Elwha Dam 2016). This created an unfavourable environment for the remaining fish, though favourable for their parasites (Elwha Dam 2016).

The Elwha Dam was built before dam licensing began to be required in 1920, but Glines Canyon Dam was issued a 50-year licence in 1926 (Winter and Crain 2008). Olympic National Park was established in 1938, with the Glines Canyon Dam being within park boundaries and the Elwha Dam outside of its boundaries (Nijhuis 2014). Although the dams fuelled economic development of the Olympic Peninsula in the early years, their hydroelectric output became less significant over time as siltation reduced electricity production and the area was connected to the wider power grid (Elwha Dam 2016). Relicensing of the Glines Canyon Dam and initial licensing of the Elwha Dam was rolled into a single procedure by the Federal Energy Regulatory Commission (FERC), and FERC was required to consider wildlife, habitat, and recreational values in addition to power generation (Winter and Crain 2008). Initially, the dams' owners objected to demolition (Winter and Crain 2008), but public support for demolition was considerable, particularly because of the dams' impact on the national park (Duda *et al*. 2008). The National Park Service determined that full restoration could only occur with removal of both dams, which would be the largest effort of its kind (Duda *et al*. 2008). In the end, the 1992 Act directing the demolition and restoration efforts was a negotiated settlement among multiple parties, including the Lower Elwha Klallam Tribe, whose lands are located at the river's mouth (Winter and Crain 2008).

The main concern for dam demolition was the downstream movement of sediment backed up in Lake Mills (16 million m^3) and Lake Aldwell (3 million m^3) (Warrick *et al*. 2012). A drawdown experiment was conducted on the Glines Canyon Dam (Elwha Dam 2016). Based on the experiment's results, a sediment erosion model was developed that predicted that a gradual drawdown could greatly reduce the downstream sediment load. Thus, a plan was developed to drain gradually over 2 years in order to keep much of the sediment in place. To accomplish this, the Glines Canyon Dam was removed over

Fig. 5. The breached Elwha Dam in Olympic National Park, Washington, United States. Image courtesy of National Park Service (public domain). https://www.google.com/search?biw=1280andbih=666andtbm=ischandsa=1andq=elwha±dam±image±public±domainandoq=elwha±dam±image±public±domainandgs_l=psyab.3.35523.42870.0.43809.26.22.0.0.0.0.159.1833.20j2.22.0.0.1.1.64.psy-ab.7.0.0.ErgctwK_OXA#imgrc=HIqRRHAbiBB0xM:andspf=1502232158449

a 3-year period beginning in September 2011 (Elwha Dam 2016), and the Elwha Dam was removed over an 8-month period (Foley *et al*. 2017) (Fig. 5). Of the 19 million m^3 of sediment, 7–8 million m^3 were expected to move downstream (Duda *et al*. 2011). However, sediment has moved more slowly than expected due to below-average precipitation (Nijhuis 2014).

Dam removal eventually restored nearly 70 miles of mainstream and tributary habitat (National Park Service 2017*a*). The slow pulsed release of fine sediment deposited minimal quantities of fine sediments on salmonid spawning habitat in the mainstream channel, but sediment deposition has severely impacted salmonid habitat in the floodplain channels (Peters *et al*. 2017). To what extent this sediment will erode over the next few years is uncertain. In addition, gravel has increased on cobble-dominated sites in the mainstream channel, making them more suitable for spawning (Peters *et al*. 2017). These changes should impact salmonid species differentially, depending on whether the particular species utilises mostly the mainstream channel or floodplain channels (Peters *et al*. 2017). Overall, salmonids have increased in abundance following dam removal, and scientists detected one new species, bull trout, as the remnant population upstream from the dams was reconnected to the river mouth. Released sediments have created 70 acres of beach and estuary habitat for Dungeness crab (*Metacarcinus magister*) and other desirable invertebrates (Nijhuis 2014), as well as for pioneer plant species, which may take decades to recover (Foley *et al*. 2017). Dam demolition has expanded the river mouth delta habitat by 400 m, reduced the influx of seawater and nutrients (P, NO_3^-, and NH_4^+) into the estuary, and shifted biological communities from brackish to freshwater species (Foley *et al*. 2017).

(5) Florida's Kissimmee River

The Kissimmee was originally a 166-km-long river, characterised by sinuous meanders and an extensive floodplain (Koebel 1995). This river flows south from Lake Kissimmee, the fourth of four major lakes known as the Kissimmee Chain of Lakes, in Osceola County, Florida. The river delivers 60% of the water feeding Lake Okeechobee. This lake, managed as a reservoir, in turn delivers water to the Florida Everglades, which in turn empties into the shallow Florida Bay (between the tip of the Florida peninsula and the Florida Keys) and ultimately into the Gulf of Mexico. In 1928, a hurricane triggered flooding from the southern shore of Lake Okeechobee, taking over 2500 lives, and in 1947, heavy rains followed by Hurricanes George and

King caused extensive flooding and property damage in the region. Consequently, in 1948 Congress authorised the Army Corps of Engineers to initiate flood control measures for south and central Florida. In 1954, Congress authorised flood control specifically for the Kissimmee River basin. From 1962 to 1971, construction converted the river into a 90-km channel known as the C-38 Canal, which consisted of five impounded pools managed for flood control. But even before construction was completed in 1971, a grassroots movement was launched to restore the Kissimmee River to a more natural state.

As a result of the channelisation, 12–14 000 ha of wetlands were lost across a floodplain that ranged from 1.5 to 3 km wide. Previously, 94% of the floodplain had been inundated at least half the time, supporting bird, fish, and invertebrate populations (Koebel 1995). Floating exotic vegetation encroached across the channel, producing large quantities of organic matter that dramatically increased biological oxygen demand. A nationally recognised largemouth bass (*Micropteris salmoides*) sports fishery was severely damaged, and wading birds declined. Only 5 years after construction was completed, the *Kissimmee River Restoration Act of 1976* was passed (Koebel 1995), launching one of the largest and most comprehensive river restoration projects in the world (Koebel and Bousquin 2014). Restoration costs are expected to reach nearly 1 billion US dollars (Koebel and Bousquin 2014).

Reestablishing the biological connection between the river channel and the floodplain created by natural inundation was deemed to be of critical importance. The trophic link between floodplain invertebrates and high trophic-level species, for example, birds and fishes, needed to be reestablished quickly (Koebel 1995). Prawns and crayfish depend on fluctuating water levels for maximal reproduction, and they move to the main channel during dry periods, supplying fish and bird populations that declined following channelisation (Dahm *et al*. 1995). Largemouth bass populations require plentiful forage fish in order to rebound, and many aquatic organisms find refuge during the dry season in 'gator holes' dug by alligators (*Alligator mississippiensis*) (Dahm *et al*. 1995).

The Kissimmee River Demonstration Project (1984–1990) was conducted on the section of the C-38 known as Pool B to determine the feasibility of backfilling the C-38 and restoring a semblance of the original course of the river (Koebel 1995). The demonstration project showed that reestablishment of a meandering channel would reinstate a diversity of stream velocities between inner and outer banks, restore a higher and more uniform dissolved oxygen content through the depth of the channel, and return a sandy bottom low in organic matter to the streambed (Dahm *et al*. 1995; Toth *et al*. 1995). Increased flow velocity was expected to rapidly generate many desirable changes to river channel habitats, but accumulation of large woody debris, important to benthic invertebrates, is not expected to accumulate to pre-settlement levels for centuries or longer (Dahm *et al*. 1995). The demonstration project also established that restoration of these hydrological features would quickly curtail proliferating populations of aquatic weeds, confine well developed littoral communities to the channel margins, and regenerate desired plant communities of broadleaf marsh, wet prairie, and buttonbush (*Cephalanthus occidentalis* L.) wetlands on the floodplain (Koebel 1995; Toth *et al*. 1995). Most importantly, the demonstration project established the feasibility of restoring the ecosystem structure and function of the Kissimmee River ecosystem at this 'grand scale' (Koebel 1995).

Following the demonstration project, scientists conducted a 3-year modelling study on physical and hydrological characteristics of the river (Koebel 1995). This study showed that backfill material returned to the channel could be sufficiently stabilised to prevent being washed downstream to Lake Okeechobee. A two-component plan was then developed to (1) revitalise the headwaters and (2) backfill the C-38 in the lower basin. Following extensive planning and restoration, construction began in 1999 to restore a meandering channel, reconnect the many oxbows, and thereby reconnect the floodplain to the main river channel with a current anticipated completion date of 2019 (Koebel and Bousquin 2014) (Fig. 6).

Of particular importance, an evaluation program was instituted to document the achievement of restoration goals. Baseline conditions were established, and realistic expectations for restoration conditions were delineated (Koebel 1995). Construction impacts and post-construction biological responses were assessed, with a provision for adaptive management (RECOVER 2017). Specifically, five critical biological communities were evaluated, namely plants, wading birds, waterfowl, fishes, and invertebrates. Also, assessments were made of taxonomic, habitat, functional, structural, and conceptual ecosystem components. This set a new standard for monitoring, as this was something that was not widely practiced at the project's beginnings (Koebel and Bousquin 2014). To date, the Kissimmee River Restoration Project has responded largely as projected in 1999, making it an example of what can be achieved by riparian restoration efforts (Koebel and Bousquin 2014).

(6) The Colorado River and its tributaries in Arizona

Tamarisk (*Tamarix ramosissima* Ledeb.), also known as salt cedar, was introduced to the United States two centuries ago (Dudley and Bean 2012). However, it was not until the early 20th century that it became widely planted as an erosion-control plant amid concerns about wind-borne soil erosion and sedimentation during an era of dam-building and agricultural expansion in the arid South-west (Stromberg *et al*. 2009; Hughes 2015). Tamarisk soon began to spread through riparian corridors (Lamberton 2012) (Fig. 7) and began to be considered as a plant that monopolises available water and increases soil salinity (Lamberton 2012). However, more recent research indicates that these concerns were mistaken and that tamarisk is more of an ecological passenger than a driver (Stromberg *et al*. 2009).

Modern dams impound spring floodwaters for release for summer irrigation in this region where agriculture would otherwise be highly restricted. Such hydrological conditions favour tamarisk but limit the native willows and cottonwoods (Stromberg *et al*. 2009; Dudley and Bean 2012). Tamarisk produces seed year round (Hughes 2015), whereas cottonwoods and willows produce seed in response to naturally occurring spring floods (Dudley and Bean 2012; Lamberton 2012; Hughes 2015). Tamarisk can remain dormant for extended periods, thereby avoiding drought, and it is highly adapted to the salty dry

Fig. 6. The original course of the Kissimmee River (left) and the C-38 canal (right) in Florida, United States. Image courtesy of Wikiwand (public domain). https://www.google.com/search?q=kissimmee±river±images±public±domainandtbm=ischandimgil=OrZo8_VIMI-WgM%253A%253BWBRiAomxo0UR4M%253Bhttps%25253A%25252F%25252Fcommons.wikimedia.org%25252Fwiki%25252FFile%25253AKissimmee_River_canal_section.jpgandsource=iuandpf=mandfir=OrZo8_VIMI-WgM%253A%252CWBRiAomxo0UR4M%252C_andusg=__EePZsDZOXmi6hT4m-vyFZBXW91E%3Dandbiw=1280andbih=666andved=0ahUKEwjZk9eXp_DVAhXjzlQKHQU9AsIQyjcINQandei=3QCfWZmxJuOd0wKF-oiQDA#imgrc=OrZo8_VIMI-WgM:andspf=1503592674321

Fig. 7. Tamarisk (left) and native willows (right) near Moab, Utah, United States. Image courtesy of United States Department of Energy (public domain). https://commons.wikimedia.org/wiki/File:Moab_Tamarisk_Removal(7468041190).jpg

channels left after water diversion (Hughes 2015). Many believe that native plants would respond favourably if natural hydrological flows were restored (Hughes 2015).

By the mid-1990s, a biocontrol for tamarisk, the northern tamarisk beetle (*Diorhabda carinulata*), had been reared, tested, and prepared for release (Dudley and Bean 2012). However, in 1995 the south-western subspecies of the willow flycatcher (*Empidonax traillii* subsp. *extimus*) was listed as endangered. Tamarisk was known to be common nesting habitat for this bird, so the beetle release was delayed pending negotiations among federal agencies. Research showed that the beetle needed a 14.5-h photoperiod to reproduce, which excluded the Arizona habitat of the subspecies (Lamberton 2012). On this basis, beetle releases began in 1999 in Utah and Nevada, but they were only permitted outside a 200-mile buffer zone from any known tamarisk nesting site (Dudley and Bean 2012). Of particular concern was the possibility that native vegetation would fail to recover once tamarisk was removed, leaving no flycatcher habitat as the tamarisk was extirpated (Dudley and Bean 2012). Other concerns were that defoliation would expose nests to predators, parasites, heating, and desiccation during the summer months.

The impact of the beetle on tamarisk was dramatic in many cases (Lamberton 2012). Thousands of hectares were defoliated two or three times in a single year by multiple generations of beetles (Dudley and Bean 2012). In 2006, weed managers introduced beetles to extreme south-western Utah along the Virgin River, a tributary of the Colorado River (Bateman *et al.* 2010). Although this location was ostensibly at the southern end of the beetle's reproductive limit, contemporary evolution allowed the beetle to expand its range southward into Arizona via riparian corridors occupied by tamarisk (Dudley and Bean 2012).

Tamarisk reduction subsequent to beetle invasion creates risks as well as restoration opportunities. For example, following tamarisk eradication from the Virgin River in Utah, flooding has caused extensive streambed erosion due to the absence of the tree and will probably impair future restoration efforts (Hughes 2015). On a hopeful note, unlike the arboreal willows, the shrubby sandbar willow (*Salix exigua* Nutt.) has remained common, and it has increased following tamarisk defoliation. Although restoration with native arboreal cottonwoods and willows is planned to mitigate the loss of tamarisk (Dudley and Bean 2012), restoration efforts are not centrally organised, so native recovery will also require natural recruitment in many cases and will likely not occur in others. A process-based restoration approach that restores hydrological conditions, thus allowing natives to thrive, probably has the greatest likelihood of success (Stromberg *et al*. 2009). In concert, 'propagule islands' may be implemented that propagate seeds to colonise downstream locations given appropriate hydrological conditions (Dudley and Bean 2012). Nevertheless, although the native trees are fast growing, the extent to which the flycatcher will occupy previously abandoned habitat remains uncertain (Dudley and Bean 2012).

Watershed ecosystems

(7) Wetlands of the Atchafalaya Basin of Louisiana

The Atachafalaya River (Fig. 8), the cultural heart of Louisiana's Cajun Country, is a significant industrial shipping route (Atchafalaya River 2017). It became the main distributary of the Mississippi River when a log jam known as the 'Great Raft' was removed in the 1840s. Because it offers a straighter and steeper path to the Gulf of Mexico than the Mississippi River's current course (Yeoman 2010*a*), if the Mississippi were left to nature today, it would revert to the Atchafalaya channel, crippling the ports of Baton Rouge and New Orleans (Atchafalaya River 2017). Indeed, the Atchafalaya River is the most recent relic course of the Mississippi (Yeoman 2010*a*), a river that has changed course many times over the centuries by oscillating like a spurting garden hose, and in so doing delivering sediments to build overlapping delta lobes at different times and at multiple locations across Louisiana's coast (Day *et al*. 2007).

In the 16th century, the Mississippi intercepted the Red River to the west, and the Atchafalaya River was formed (Mossa 2016). In 1831, Captain Shreve installed a cutoff at a meander bend near the town of Simmesport to improve navigation, thereby creating the Upper and Lower Old Rivers, which connect the Mississippi River to the east with the Red and Atchafalaya Rivers to the west. In 1954, the Morganza Spillway was completed to divert high

Fig. 8. The Atchafalaya River. Image courtesy of United States Army Corps of Engineers (public domain). https://commons.wikimedia.org/wiki/File:Atchafalaya_Basin.jpg

water from the Mississippi into the Atchafalaya as needed for flood control, for example, for the 1973 and 2011 floods (2011 Mississippi River floods 2017). In 1963, the Old River Control Project was completed, with a lock and dam to allow navigation between the Mississippi and Atchafalaya Rivers and to maintain the current course of the Mississippi.

According to the Environmental Protection Agency (EPA), Louisiana may lose one-third of its coastal land by 2050 (Yeoman 2010*b*). The mainland is eroding due to insufficient protection from receding wetlands as tropical storms and hurricanes batter the coast (Yeoman 2010*c*). Although the lower Mississippi River is mostly leveed, the Atchafalaya is mostly free. The Atchafalaya Basin consists of 1.4 million acres and is the doorway to the Mississippi Flyway. During flooding, sediments can wash over the banks of the Atchafalaya River to replenish lands that would otherwise sink. Today, its two deltas, the main channel and Wax Lake Outlet, an artificial channel constructed in 1938–41 to protect Morgan City from flooding (Mossa 2016), are the only parts of the Louisiana coast that are not losing wetlands to open water (Yeoman 2010*a*; Rosen and Xu 2013; Mossa 2016; Atchafalaya River 2017). Deltas in the shallow Atchafalaya Bay began to emerge after the 1972 flood and have continued to grow (Rosen and Xu 2013; Mossa 2016).

Human activities have impacted coastal Louisiana in four major ways. Leveeing the Mississippi River for flood control and navigation has excluded land-building sediment, dredging of 15 000 km of canals has provided routes for saltwater intrusion, oil and gas extraction has led to land subsidence, and climate change has raised sea level (Day *et al*. 2007; Yeoman 2010*c*; Rosen and Xu 2013). Coasts need sediment to build deltas and prevent saltwater intrusion, and wetlands and swamps are needed to provide hurricane protection (Yeoman 2010*a*). Levees and industrial canals have shrunken coastal marshes, limiting their ability to absorb storm surges moving across the land, which cause erosion and kill vegetation due to extended saltwater intrusion into freshwater marshes (Gaskill 2008; Rosen and Xu 2013). Since the 1930s, Louisiana has lost 1.3 million acres (Yeoman 2010*a*), forcing an estimated 10 000 Louisianans to migrate northward (Yeoman 2010*c*). However, aggradation in the Atchafalaya Basin inspires hope that navigation and delta-building might coexist (Yeoman 2010*a*).

Landforms in coastal Louisiana are modified by natural forces. Cold fronts may flush water and move sediment (Rosen and Xu 2013), and tropical storm systems may stimulate large flows of fresh water and deposit sediment (Day *et al*. 2007). However, other effects of storms may not be so desirable. In 2005, Hurricane Katrina knocked down an estimated 320 million large trees on the Gulf Coast across an area the size of Maine (Gaskill 2008). Although Hurricane Andrew (1992) added sediment, Rita (2005) enlarged ponds (Rosen and Xu 2013). The two 2005 hurricanes (Katrina and Rita) converted 100 km^2 of wetlands to open water in the Breton Sound near the terminus of the Mississippi River, despite depositing considerable sediment elsewhere (Day *et al.* 2007).

Floods bring nourishing sediment but, on occasion, great human peril. The Great Mississippi Flood of 1927 was the most destructive flood in United States history (Great Mississippi Flood of 1927 2017). Approximately 500 were killed in the Mississippi Delta region considerably farther north upriver, and 700 000 were left homeless. About 200 000 African Americans were relocated to relief camps, and many of these eventually joined the Great Migration north to Chicago and other northern cities. The subsequent *Flood Control Act of 1928* led to construction of the world's largest system of levees and channels. Channelling reduced the land's absorption of seasonal rains, thus subsequent major flood events in 1973, 1993, and 2011 were less destructive. However, channelling also increased current velocity, thereby reducing sediment deposition. Larger flood events are more effective at sediment delivery downstream, particularly of coarse sediments that can fuel delta growth by capping fine sediment deposits to create an elevated substrate (Rosen and Xu 2013). Such land is much more likely to stabilise if it becomes vegetated due to both the vegetation itself and to soil strength conferred by dense roots (Rosen and Xu 2013). However, sediment loads on the Mississippi River (Yeoman 2011) and the Red River (Mossa 2016) have been declining for some time due to reservoirs and soil conservation measures upstream.

To fulfil its flood control mandate, the policy of the United States Army Corps of Engineers is to deliver 30% of the Mississippi River flow into the Atchafalaya, with the rest remaining in the Mississippi (Yeoman 2010*a*; Kozak *et al*. 2016; Atchafalaya River 2017). In 1928, the Atchafalaya River was designated as the principal floodway of the Mississippi River (Kozak *et al*. 2016), a decision that has proven beneficial for both flood control and the environment (Yeoman 2010*a*). However, this designation has led to engineering modifications to the Atchafalaya Basin that have disrupted the connection between the river and the swamp. These include the erection of flood-protection levees in the upper portion of the river that have reduced the Basin to 26% of its original size, the cutting off of 22 distributaries, and the construction of new channels for freshwater distribution (Kozak *et al*. 2016). Approaches to ameliorating these modifications include connecting the river to the delta plain on a large scale; applying dredged sediments to create or restore wetlands; restoring barrier islands by pumping offshore sands; and restoring hydrological processes by removing spoil banks that hinder sheet flow, backfilling canals, closing deep navigation channels, installing locks, and trapping sediments (Day *et al.* 2007; Yeoman 2011). Yet such actions must be applied within the context of a working waterway.

The bald cypress (*Taxodium distichum* [L.] Rich.) – water tupelo (*Nyssa aquatica* Marshall) swamp forest ecosystem, important for commercial crawfishing, makes up 43% of the lower Atchafalaya Basin (Kozak *et al*. 2016). However, regeneration of these trees is precluded by the permanently inundated state induced by floodway management policy, which is to maintain the 30% diversion to the Atchafalaya on a daily basis. Although the bases of adult trees of these two species can live several hundred years under submerged conditions, seeds must germinate above water and seedlings can be killed by prolonged submergence. Kozak *et al*. (2016) have offered an environmental flow prescription that favours forest regeneration yet meets the management needs of a working river. This prescription provides for regulating the 70/30 diversion on a monthly rather than daily basis to ensure that sufficient water is present in the spring to provide fish with access to the floodplain and to prevent hardwood invasion. Conversion of cypress-tupelo swamp to hardwood bottomland forest occurs when sediment is deposited upriver rather than being transported to the coast where it can build deltas (Yeoman 2010*a*). The prescription also ensures low water in the summer to maximise productivity and forest regeneration. A separate threat to cypress has been logging for mulch, a practice that was eventually curtailed when retailers ceased sales in 2007 (Yeoman 2010*a*).

Chinese tallow (*Triadica sebifera* [L.] Small) is an escaped ornamental tree (Yeoman 2010*b*), originally introduced by Benjamin Franklin from China in 1776 (Urbatsch 2000). Its tremendous seed production and its ability to resprout from stumps and roots have made it difficult to control (Urbatsch 2000). Proliferation of this weedy tree has eliminated habitat for the highly endangered Attwater subspecies of the greater prairie chicken (*Tympanuchus cupido* subsp. *attwateri*) (Urbatsch 2000). High-elevation spoil mounds, a legacy of canal construction, are ideal for Chinese tallow, as this plant cannot persist on low ground (Yeoman 2010*c*). To restore infested areas, trees are bulldozed with excavators mounted on pontoon platforms and then dumped into canal bottoms along with dirt from the spoil mounds (Yeoman 2010*b*).

Before 2005, planning for restoration was separate from that for storm protection and navigation, but fortunately the fallout from the 2005 hurricanes has changed that (Day *et al*. 2007). These storms removed social obstacles to aggressive action, and it is now generally appreciated that action on an unprecedented scale is required. And this may be forthcoming. The *Gulf of Mexico Energy Security Act of 2006* provides that 37% of revenues from new oil and gas operations go to coastal states, with Louisiana dedicating its share to coastal restoration. British Petroleum's final bill for the 2010 Deepwater Horizon oil spill came to $20.8 billion, with $14.9 billion going to restoration, including $8 billion to Louisiana (Marshall 2015). Payments begin in 2017 and are spread over 15 years. Hopefully the expenditure of these funds will lead to a more sustainable ecological future for coastal Louisiana.

(8) The Chesapeake Bay and its watershed in the mid-Atlantic states

The Chesapeake Bay is the largest estuary in the USA (Snider 2016). Its watershed consists of parts of six states and the District of Columbia (Chesapeake Bay 2017). The Bay formed at the end of the Pleistocene as the bed of the Susquehanna River flooded with rising seas (Chesapeake Bay 2017). Major pollutants are N, phosphorus, and sediment (Chesapeake Bay Program 2016), and an anoxic dead zone was found as early as the 1970s (Chesapeake Bay 2017). Best management practices to control these pollutants include upgrading wastewater treatment plants, lowering vehicle and power plant emissions, and reducing farm runoff (Chesapeake Bay Program 2016).

Flowing through New York, Pennsylvania, and Maryland, the Susquehanna River provides about half of the freshwater input into the Bay. Half of the N entering the Bay originates in Pennsylvania (Snider 2016). Government payments have encouraged the planting of 125 000 acres of forested buffers along riparian corridors to filter out nutrients from agricultural runoff (Snider 2016). On its Maryland property, the Smithsonian Institution has installed meanders, weirs, and rock berms to slow water velocity and generate pools (Wheeler 2016*a*). Filling gullies and removing legacy sediments that have disconnected the channel from the floodplain has increased nutrient absorption and restored wetlands to a more natural state (Wheeler 2016*a*). Under pressure from the federal EPA, states have been required to write and implement clean-up plans under the Clean Water Rule, but because remaining sources of pollution are non-point-source and the watershed is large, progress has been slow. The American Farm Bureau Federation has sued, but so far the courts have sided with the EPA, with the Supreme Court recently declining to hear the case (Snider 2016). However, in February 2017 the month-old Trump Administration announced plans to withdraw the Clean Water Rule via executive order (Leibowitz 2017).

Common reed (*Phragmites australis* [Cav.] Trin. *ex* Steud.), native to both the Old World and New World, may be the most widely distributed flowering plant species in the world and is now found in every state except Alaska (Tilley and St. John 2012). This grass may be found in freshwater to saline environments and spreads primarily through rhizome fragments rather than seed (Kettenring *et al*. 2010; Tilley and St. John 2012), though the latter may contribute to spread by increasing genetic recombination (Kettenring *et al*. 2010). In this peculiar situation, we have an alien European population that has become highly invasive once introduced to North America (Chambers *et al*. 1999). This has led to the eradication of its native conspecific counterparts throughout the expanding range of the invader (Saltonstall 2002) and to a loss of associated flora and fauna (Chambers *et al*. 1999). It is this plant material that has become problematic in Chesapeake Bay and its tributaries (Kettenring *et al*. 2010). The invasive and native forms can be distinguished on the basis of floral and culm traits with a dichotomous key (Tilley and St. John 2012). However, the invasive type is also distinguished by its greater photosynthesis, stomatal conductance, canopy size, specific leaf area, N content, and 4-fold greater requirement for N, making it a more effective competitor than the native population (Mozdzer and Zieman 2010). Thus, it is likely that anthropogenic eutrophication of waterways has enabled the spread of the invasive material. *Phragmites* can be controlled by foliar sprays and stem injections of glyphosate, but eradication in practical terms is unlikely for large patches (>3000 m^2), so detection and treatment of new small patches is advised (Quirion *et al*. 2017).

Eelgrass (*Zostera marina* L.) is the dominant seagrass in the Bay, and it provides food for waterfowl; habitat for blue crab (*Callinectes sapidus*), bay scallop (*Argopecten irradians*), and juvenile striped bass (*Morone saxatilis*) (Orth *et al*. 2010; Virginia Institute of Marine Science 2017); and protection for a variety of fauna from predatory fishes and crabs (Orth *et al*. 1984). Eelgrass is considered a 'coastal canary' (Devitt 2017), and its extent in the Bay has been reduced by over half since the early 1970s (Chesapeake Bay 2017) as water clarity has diminished (Orth *et al*. 2010). Runoff generated by Tropical Storm Agnes (1972) eliminated extensive areas of eelgrass (Orth *et al*. 2010). Most eelgrass restoration efforts have utilised transplants with meagre success, though good results have been achieved in nearby Virginia coastal bays where the water is cooler and nutrient loading is lower (Orth *et al*. 2010; Oreska *et al*. 2017). Protocols and technology for mechanical seed harvest, storage, and mechanical planting have recently been developed, holding promise for the future (Marion and Orth 2010).

Chesapeake Bay is famous for its seafood, but stocks have struggled for decades. The most profitable commercial fishery is the blue crab (Cutlip 2016) (Fig. 9). Crab populations fluctuate dramatically, and a decade of low numbers has typically been followed by a recovery (Stagg and Whilden 1997). Crab stocks are currently good, having recovered from a record low in 2007 (Cutlip 2016). In this case, research found that stocks were recruitment limited, so winter dredge harvesting was prohibited in 2008 to protect females (Cutlip 2016). Year-round hatchery production of larvae and juveniles is now possible, with survival in the wild similar to wild crab (Zohar *et al*. 2008). The striped bass (Maryland's state fish) fishery nearly collapsed in the 1980s, but this anadromous fish has recovered following fishing moratoria in Maryland and Virginia (Elliott 2015). Virginia had a short-lived bay scallop industry in the early 1930s, which was lost simultaneously with the loss of eelgrass (Oreska *et al*. 2017). Now that eelgrass restoration is seeing some success in Virginia coastal bays, bay scallop restoration may be feasible (Oreska *et al*. 2017). However, as bay scallops are harvested by dredging, which disturbs eelgrass stands, harvests should be limited to bare areas, leaving eelgrass areas as nurseries for scallop recruitment (Oreska *et al*. 2017).

Eastern oysters (*Crassostrea virginica*) are ecosystem engineers that filter nutrients, plankton, and detritus (Schulte *et al*. 2009), with the potential to process 50 gallons per day per oyster, thereby greatly improving water quality and clarity (Eastern oyster 2017). Eastern oyster populations peaked in Chesapeake Bay in the 1880s, with declines since that time due to overfishing and reef destruction (Schulte *et al*. 2009). Current populations in the Bay are considered to be ~1% of historic levels (Eastern oyster 2017). Oyster restoration success had been wanting until a recent discovery that artificial cage reefs that extend 25–45 cm above the stream bottom were much more successful in oyster abundance and density than the shorter reefs that had been in use (Schulte *et al*. 2009). These high reefs are exposed to more desirable stream flows and are positioned away from stream-bottom sediments, resulting in oysters that are physiologically healthy, are free of disease, and display favourable rates of growth, survival, and juvenile recruitment (Schulte *et al*. 2009). Two diseases have plagued oyster production, but natural resistance has been found in reef sanctuaries in the lower part of the Bay (Schulte *et al*. 2009).

Fig. 9. Blue crabs from the Chesapeake Bay, United States. Image courtesy of the Chesapeake Bay Program (public domain). https://www.google.com/search?q=Chesapeake±Bay±public±domain±imageandtbm=ischandtbo=uandsource=univandsa=Xandved=0ahUKEwjlmIPd1sjVAhWqs1QKHYm-B-4Q7AkIMgandbiw=1280andbih=66#imgrc=2e0-BD-dWf-AiM:andspf=1502231116454

Harris Creek, on Maryland's eastern shore, boasts the largest artificial oyster reef (330 acres) (Fears 2015). Oyster shells are recycled from restaurants for use as substrate and loaded into high-relief cages, which are then submerged and colonised *ex situ* by spat (larvae). When the oysters reach sufficient size, they are lowered into the stream as an artificial reef. It is now believed that artificial reefs must be protected from harvest in order to establish (Schulte *et al*. 2009), and they have been largely built in state-protected sanctuaries (Wheeler 2016*b*). This has created a conflict with the commercial fishing interests (Wheeler 2016*b*).

Currently, ecological condition of the Chesapeake Bay appears to be on the upswing, though this may be partly due to favourable weather in 2016 (Cox 2017). Blue crab harvests are up, and anoxic zones have diminished. Poultry farms have implemented nutrient management plans to limit N and phosphorus runoff, and state subsidies are available for seeding cover crops and hauling manure.

(9) The tallgrass prairie of the Midwest, its Corn Belt replacement, and the impacted Gulf of Mexico downstream

The tallgrass prairie once occupied 240 million acres, but now less than 3% of these lands remain intact (Smith 1990). Nearly all of this loss occurred in the 19th century. But locally, the loss was much more rapid, with prairie surviving less than 20 years once a particular area was opened to settlement. Settlement in Iowa began in 1833 following defeat of the Sauk tribe. But from 1865 to 1890, following the Civil War, agricultural settlement was completed to the western edge of the tallgrass prairie in states further west. Settlement was facilitated by many factors including fertile prairie soils, advances in farm machinery (particularly plows), drainage of wetlands, extension of rail and steamboat service, a sizeable population of ex-soldiers and European immigrants, and the *Homestead Act of 1860*, which offered land to settlers. In 1900, most Iowa counties recorded their maximum number of farm units, and destruction of the tallgrass prairie ecosystem was complete in that state.

For the past 30 years, the USDA-administered Conservation Reserve Program (CRP) has provided financial incentives to retire marginal cropland, replacing it primarily with native perennial grasses. However, high prices for agricultural commodities and improved crop varieties have created incentives to convert native prairie and CRP lands back to corn and soybean production (Wright and Wimberly 2013). Part of the reason for high commodity prices is United States policy to increase corn production for biofuel (ethanol) production, specifically the *Energy Independence and Security Act of 2007*. Conca (2014) reported that the percentage of the United States corn crop used for ethanol production rose from <5% in 2000 to 40% in 2013, despite evidence that the fossil energy required to produce ethanol from corn is 29% greater than the energy in the ethanol itself (Pimentel and Patzek 2005). A historic 22% increase in United States maize acreage occurred from 2006 to 2007, with acreages since then ranging from 12% (2015) to 24% (2012) higher than the 2006 baseline (Y-charts 2016). Consequently, Wright and Wimberly (2013) reported a net loss of 530 000 ha of perennial grass cover from 2006 to 2011 across five states in the western Corn Belt. These lands, which have been replaced with corn and soybeans, are marginal for agriculture, being susceptible to erosion and drought. In addition, they are often proximal to the wetlands of the Prairie Pothole Region, which provide important nesting habitat for migratory waterfowl.

The anoxic 'dead-zone' in the Gulf of Mexico reached a record size of 22 720 km^2 in 2017, surpassing the previous record set in 2002 (McConnaughey 2017). The size of the dead-zone, which has a detrimental effect on Louisiana's shrimp industry, is larger in wet years because more nutrient-laden water moves down the Mississippi River (McConnaughey 2017). The dead-zone is fed by nitrates that originate primarily on the agricultural lands of the Mississippi Basin and are delivered to the Gulf via the Mississippi and Atchafalaya Rivers (Mitsch and Day 2006). This drainage accounts for 80% of the United States corn and soybean acreage (Donner and Kucharik 2008) and 40% of the world's corn production (Asbjornsen *et al*. 2014). It is estimated that N-fertiliser use increased 20-fold from 1953 to 2003 (Glass 2003). However, crops are generally able to utilise only 30–40% of the N applied (Kant *et al*. 2011), though modern maize hybrids exhibit an improved response to N supply (O'Neill *et al*. 2004). Most N losses occurring through subsurface drainage (McLellan *et al*. 2015), hence N loads on the Mississippi River have continued to increase (McLellan *et al*. 2015). In addition to high N load, eutrophication has also been favoured by rapid and efficient drainage improvements, allowing cropland expansion, and the separation of the Mississippi River from its natural floodplain by physical structures (Mitsch and Day 2006).

Several researchers have considered how to address the dead-zone in the Gulf of Mexico. Remediation of Gulf hypoxia likely requires a 45% reduction in N load, which necessitates a two-pronged approach that includes both N-management, for example, rate, timing, and method of N-fertiliser application; cover crops; and N-removal treatments, for example, constructed wetlands, drainage ditch enhancements, stream restoration, and floodplain reconnection (McLellan *et al*. 2015). Nitrification inhibitors, for example, nitrapyrin, can inhibit the conversion of ammonium to nitrite by *Nitrosomonas* bacteria, thereby making more N available to the crop and reducing secondary conversion of nitrate to nitrite (IPNI 2017), which is a major contributor to eutrophication of wetlands and waterways (Mitsch and Day 2006). Mitsch and Day (2006) recommended a strategic restoration of 2.2 million ha of wetlands, including in-field wetlands to function as N-sinks for agricultural runoff and diversion wetlands to accommodate river flooding. These improvements plus nitrate reductions from improved agronomic practices would be sufficient to decrease the size of the dead zone. Additional benefits would include lowered nitrates in drinking water, habitat restoration, flood control, and protection of agriculture from additional environmental regulatory action.

Annual overwintering cover crops are an example of a 'win-win' situation for agriculture and the environment, thus they are being rapidly adopted throughout the region (Arnason 2017). For example, Iowa growers autumn-seeded cover crops on 35% more acreage in 2016 than in 2015. Livestock may graze cover crops, extending the grazing season and improving cattle condition before calving (Carrico 2017). Because they replace the fallow period, cover crops may improve soil health, minimise soil losses of N and phosphorus, and boost yields of erosion-prone row crops. In a long-term experiment in central Italy, cover crops increased soil N and soil organic carbon (C), and this effect was additive to such benefits that accrued due to the use of no-tillage relative to conventional tillage (Mazzoncini *et al*. 2011). Cropped soils are C-depleted relative to wildland soils, but a meta-analysis found that seeding a cover crop each year could continue to increase soil organic C for 155 years of crop cultivation (Poeplau and Don 2015). Across 5 years in a corn-soybean rotation in Ontario, nitrate losses were reduced by 15% with a wheat cover crop, by 39% with controlled tile drainage with subirrigation (relative to traditional unrestricted tile drainage), and by 47% with the combination of these two practices. Tile drainage facilitates early planting and late harvest, but as traditionally practiced, it also transports nutrients from farm fields into ditches and eventually streams. Farm-level bioreactors can treat tile-drained runoff water in underground trenches filled with wood chips, where bacteria convert nitrates into N gas, which is ultimately released harmlessly into the atmosphere (Gaul 2017).

Increased use of perennial vegetation has been suggested as a partial solution for restoring soil C and N and minimising nitrate loading in the watershed (Asbjornsen *et al*. 2014). Perennials offer an alternative to annual grains for biofuel production (Gelfand *et al*. 2011; Wright and Wimberly 2013). Natural perennial cover intercepts, retains, and uses more precipitation than annual crops, whereas the greater root mass of the perennials stores more C, while losing 5X less water and 35X less nitrate (Glover *et al*. 2010*b*). Although annual cropping is viable in terms of N use for the first few years following the first tillage, yields subsequently decline (Glover *et al*. 2010*a*). However, soils beneath perennial grasses in Britain retained a consistent level of N indefinitely (Jenkinson *et al*. 2004) and biomass yields did not decline (Jenkinson *et al*. 1994). Minnesota is implementing a program to buy perpetual easements from farmers that will be planted with native perennial species (Bjorhus 2017). The state's new buffer law requires perennial vegetation planted along watercourses to prevent erosion and limit nutrient loading in runoff.

To provide an environmentally friendly perennial alternative to annual cropping systems, The Land Institute (Salina, Kansas) aims to develop viable perennial grain crops for the region. Kernza is being bred as a speciality perennial grain from the perennial forage grass and close wheat relative, intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D. R. Dewey) (Glover *et al*. 2010*b*; Lubofsky 2016). Kernza now qualifies for use in Minnesota's perennial buffers (Minnesota 2017). Soil nitrate levels under kernza were nearly undetectable for the first reproductive year (Culman *et al*. 2013). Soil C mineralisation, an indirect measure of soil C sequestration, was greater for kernza than for wheat. However, kernza grain yields in the first reproductive year were only one-third that of wheat.

Tallgrass prairie (Fig. 10) restoration is widely practiced and relatively well developed in the Upper Midwest (Rowe 2010).

Fig. 10. Forbs in the tallgrass prairie. Image courtesy of the United States Fish and Wildlife Service (public domain). https://upload.wikimedia.org/wikipedia/commons/a/a3/Flowering_wildflowers_in_tall_grass.jpg

The four most frequent native grasses of the tallgrass prairie are big bluestem (*Andropogon gerardii* Vitman), little bluestem (*Schizachyrium scoparium* [Michx.] Nash), switchgrass (*Panicum virgatum* L.), and indiangrass (*Sorghastrum nutans* [L.] Nash). Inclusion of native forbs in prairie seed mixes is realising increased impetus due to the current emphasis on pollinator recovery (Obama 2014), and seed mixes may be designed to support native bee populations (Harmon-Threatt and Hendrix 2015; Cane and Love 2016). Restoration species may be seeded on fallow land, but prior efforts must be taken to control exotic grasses (Rowe 2010). If seeded directly following a crop, following soybean is preferred over following corn because the former leaves less residual N to stimulate weed growth (Rowe 2010). Prescribed fire is used to control the encroachment of woody species, whereas fire, mowing, grazing, and reduced grass seeding rates can be used to increase forb diversity (Rowe 2010).

Conclusion

Together, these nine case studies tell a vibrant story of ongoing restoration efforts in the USA. But perhaps more importantly, they point to a future of vitality for such efforts. These case studies address restoration projects that are large and notable in one or more categories, for example, their scope, complexity, expense, planning efforts, monitoring activities, use of computer modelling, and number and diversity of partners. Furthermore, several of the case studies provide examples of how ecologists can interface with agriculturalists or engineers to rectify problems that have emanated from past manipulations that historically served society's needs but no longer have the value they once did. Several of the case studies show how landowners, non-profit organisations, and state and federal agencies can work together to make progress towards both regulatory standards and restoration goals, thereby precluding the triggering of more restrictive regulations. Examples include the restoration of shrubland habitat for the greater sage-grouse and installation of buffer strips in the Corn Belt and the Susquehanna Valley (Chesapeake Bay watershed) to combat non-point-source pollution due to nutrient-laden agricultural runoff. This is good news for the environment and the restoration community, as the public can be expected to be supportive of efforts to rejuvenate Nature when it can see the results in its own backyard.

Major restoration projects are attracting the attention of a larger and more diverse array of professionals and professions than ever before. Thus, a more robust community will exist to share stories of success and failure. Development of ecological restoration methodology will continue to be a trial-and-error process. But experimental research will play a larger role as the discipline continues to mature and the collective experience of restoration ecologists and practitioners accumulates.

Finally, restoration efforts are almost always limited by available funding, but it will be interesting to see what will transpire in Louisiana coastal restoration, where an abundance of funds is becoming available. In general, it is unlikely that funding for restoration efforts will increase perpetually, though a silver lining is that limited funding may drive the discovery of more cost-effective techniques. Nevertheless, additional funds are ultimately likely to become available as the frequency of restoration successes increases.

Conflicts of interest

The author declares no conflicts of interest.

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