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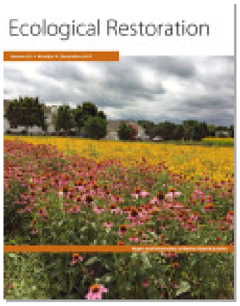

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ABSTRACT

In 1998, a riparian restoration demonstration project was initiated with a target of efficiently establishing a dynamic patch mosaic of vegetation communities along a regulated river using available water and sediment and remaining natural hydrological processes. A point bar along the Middle Rio Grande, Albuquerque, New Mexico, dominated by the non-native shrub *Elaeagnus angustifolia* (Russian olive), was mechanically treated by removing all vegetation and lowering a portion of the bar to allow overbank flooding during typical spring releases from an upstream dam (Cochiti Dam). Side channels and small islands were engineered in the lowered bar to slow flood waters, aid sediment deposition, and add site complexity. After treatment, a high-resolution monitoring grid was installed to track vegetation changes. Following an initial flood in the spring of 1998, over 10,000 cottonwoods per ha naturally established, but densities varied based on the fluvial landforms. Zones that were sufficiently wetted or naturally formed behind large woody debris were the most successful, while the artificial fill zone and the portion of the bar not lowered had the least native riparian tree recruitment. Over 15 years, cottonwood numbers declined through intraspecific competition and beaver browsing at all sites, but they continued to dominate. Natives also dominated a species-rich herbaceous layer, particularly on the lowered sites. The incursion of a new herbaceous invader, *Saccharum ravennae* (ravennagrass), was an unexpected outcome revealed by the long-term monitoring record. Yet, based on several criteria, the site reflects a successful application of a natural-process approach to restoration that can lead to increased ecosystem complexity and resilience.

Keywords: dynamic patch mosaic, *Populus deltoides* var. *wislizenii*, *Elaeagnus angustifolia*, *Tamarix* spp., *Saccharum ravennae*, beavers, vegetation monitoring

Natural-process approaches to riparian restoration have gained broader acceptance as tools for generating and maintaining native vegetation diversity, providing supporting habitat for fish and wildlife, and enhancing overall ecological services (Stanford et al. 1996, Poff et al. 1997, Molles et al. 1998, Stromberg 2001, Follstad Shah et al. 2007, Stromberg et al. 2007a, Beechie et al. 2010). A guiding principal of this approach is restoration of dynamic riverscapes of shifting ecological communities in the context of a changing fluvial geomorphic template (Crawford et al. 1993, Hupp and Osterkamp 1996, Crawford et al. 1999, Richter and Richter 2000, Latterell et al. 2006, Brierley et al. 2010, Weisberg et al. 2013). That is, restoration should foster a dynamic patch mosaic of vegetation succession intertwined with the evolution of fluvial surfaces in response to flooding and channel migration. For example, sites should encompass young, freshly deposited river bars supporting pioneer herbaceous vegetation and shrublands as well as mature riparian forests on terraces that may no longer be flooded. In addition, pursuing the reestablishment of a dynamic patch mosaic holds the potential for being the most cost-effective approach to restoration by letting the river do the bulk of work in a way that leads to the long-term sustainability of a complex and relatively natural ecosystem (Stanford et al. 1996, Taylor and McDaniel 1998).

This is particularly pertinent in the southwestern U.S., where regulated lowland river systems have been extensively invaded by woody, non-native *Elaeagnus angustifolia*

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Restoration Recap

- Mechanically manipulating a site on a regulated river to take advantage of available post-dam flows, sediments, and large woody debris can lead to the development of a native-dominated, reinvigorated riparian zone.
- Designs should encompass a diversity of fluvial geomorphic landforms but avoid constructing elements that do not mimic natural processes.
- To be cost-effective, bank-lowering riparian restoration sites should be carefully selected. For example, places associated with highly entrenched or dewatered channels can drive costs up along with the level of risk.
- Retreatment of invasive species at a periodic but manageable level may still be required.
- Long-term monitoring is critical for adapting to changing conditions on a restoration site. and for evaluating the efficacy of the project as a whole per the recommendations of Palmer et al. (2005) and Follstad Shah et al. (2007): 1) a guiding image of the dynamic state; 2) improved ecosystems; 3) increased resilience; 4) no lasting harm; and 5) a completed ecological assessment.

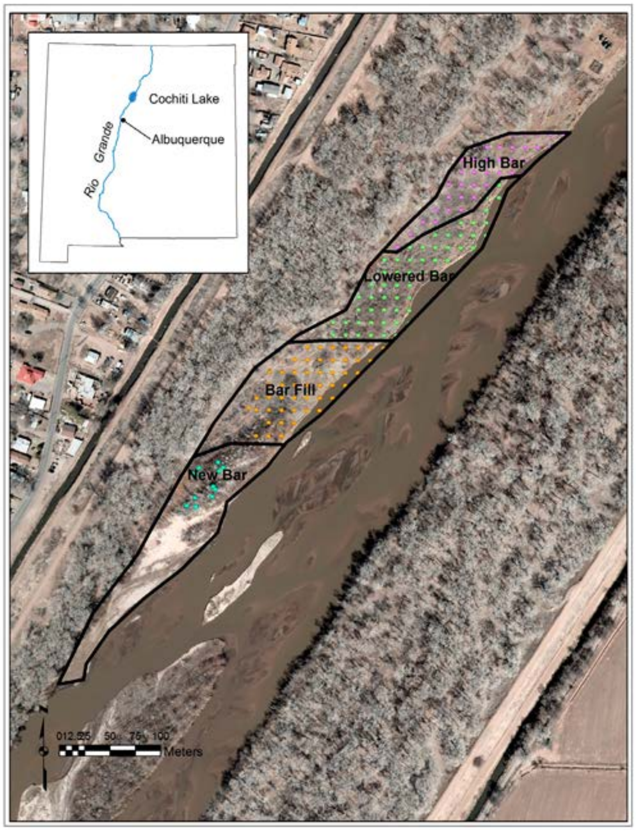

Figure 1. The Albuquerque Overbank Project is located in the middle reach of the Rio Grande in north-central New Mexico, USA and 50 km south of the Cochiti Dam, which regulates flood flows. The restoration site was established at the southern end of a point bar in the urban Albuquerque sub-reach. There are four treatment zones overlain by a random-systematic sampling point grid.

(Russian olive) and *Tamarix* spp. (tamarisk). This presents a daunting task for restoration (Everitt 1998, Stannard et al. 2002, Cooper et al. 2003, Shafroth et al. 2005, Friedman et al. 2005, Reynolds and Cooper 2010). The classical and still predominant approach is to remove the woody invaders with a combination of herbicide, stem cutting, or root plowing followed by pole plantings of native phreatophytes such as cottonwoods and willows (Brock 1998, 2003, Stannard et al. 2002, Katz and Shafroth 2003). While effective in the short-term, sites often return to an exotic-dominated state because nothing has changed with respect to the hydro-geomorphic configuration of the site and the associated stream-flow regime (Hultine et al. 2010, Shafroth et al. 2005). Accordingly, restoration practitioners in the southwestern U.S. have been embracing a natural-process approach to large rivers as potentially more cost-effective in establishing and sustaining a native-dominated, diverse, and productive riparian ecosystem (Follstad Shah et al. 2007).

Water, sediment, and seed availability along with the fluvial-geomorphic complexity are key factors in a natural-process approach to restoration. For example, in lowland rivers of the southwestern U.S., one of the crucial elements is creating conditions that meet recruitment requirements for cottonwoods such as *Populus deltoides* var. *wislizenii* (Rio Grande cottonwood) and *P. fremontii* (Fremont cottonwood) and willows such as *Salix gooddingii* (Goodding's willow), *S. amygdaloides* (peachleaf willow), and *S. exigua* (coyote willow), and doing so at the right time (Stromberg 1997, Bhattacharjee et al. 2006, Taylor et al. 2006, Bhattacharjee et al. 2008). This calls for sites that can be flooded during spring runoff which also have a substrate conducive to germination of the current seed crop, followed by rapid to moderate drawdown, but a sufficiently shallow water table to ensure establishment and sustainability of the young trees and shrubs (Taylor et al. 1999). In addition, the goal is also to create a degree of geomorphic complexity that leads to the development of a complex mosaic of communities, not just monotypic cottonwood and/or willow stands (e.g., emergent wetlands, meadows, etc.; Weisberg et al. 2013). Lastly, we want to reinitiate the natural processes within current constraints so as to generate a cascade of positive effects in the reach as well as on-site processes that lead to a dynamic, sustainable river ecosystem in the long term.

To help evaluate the efficacy of this natural, process-based approach in a large, regulated river, we initiated a demonstration project in 1998 known as the Albuquerque Overbank Project (AOP) located on a point bar dominated by non-native *Elaeagnus* in the urban Albuquerque reach of the Middle Rio Grande in central New Mexico (Figure 1). Due to a large dam (Cochiti Dam), flood control measures, and extensive agriculture and municipal diversions, the Middle Rio Grande has been highly altered over the past century. There has been significant channelization and reduced lateral migration (Richard et al. 2005), flow and sediment delivery modifications (Richard and Julien 2003, Ortiz 2004; Supplementary Figure 1) with concomitant changes in the fluvial geomorphic structure of the channel and associated floodplain (Lagasse 1981, Porter and Massong 2004, Tashjian and Massong 2006, Makar and AuBuchon 2012).

Despite these hydrologic and geomorphic impacts, many of the essential elements of riparian functionality and biodiversity are still extant, which can be used to advantage in ecological restoration. There are still spring peak flows driven by snowpack, although they are smaller by 38%—declining from an average of 218 CMS (7,700 CFS) over the 80 years prior to Cochiti Dam closure in 1973 to 136 CMS (4,800 CFS) in the ensuing 25 years (Richard and Julien 2003). While peaks have declined in size, the duration has increased under regulation, but the remaining higher flows do not reach as far into mid-summer as they did historically (Molles et al. 1998; Supplementary Figure 2). Later in summer on through winter and in non-drought years, there is a more-or-less consistent regulated base flow (22 CMS;760 CFS) from year to year augmented by episodic large, sediment-laden flows from tributary desert washes (arroyos) during thunderstorms. These on occasion can generate peak flows similar to the spring runoff period (Supplementary Figure 2). The summer base flow supports dense vegetation on point bars and islands, and an extensive riverside mature cottonwood forest that is one of the largest in the Southwest. Our goal was to take advantage of those remaining attributes and mechanically augment those that are severely limited at present (e.g., scouring floods and significant channel lateral migration) by clearing the site, physically lowering portions of the bar to facilitate overbank flooding, and then engineering channels and islands to create geomorphic heterogeneity and encourage sediment deposition as a seedbed for native vegetation, including cottonwoods and willows.

Simultaneously, we installed a high-resolution vegetation-monitoring grid that has provided one of the longest records of vegetation change in a riparian zone in the Southwest (16 years to date). We report here on some of the insights and surprises that this relatively long record has provided with respect to natural-process restoration and evaluate project outcomes in the context of general restoration goals recommended by Palmer et al. (2005)

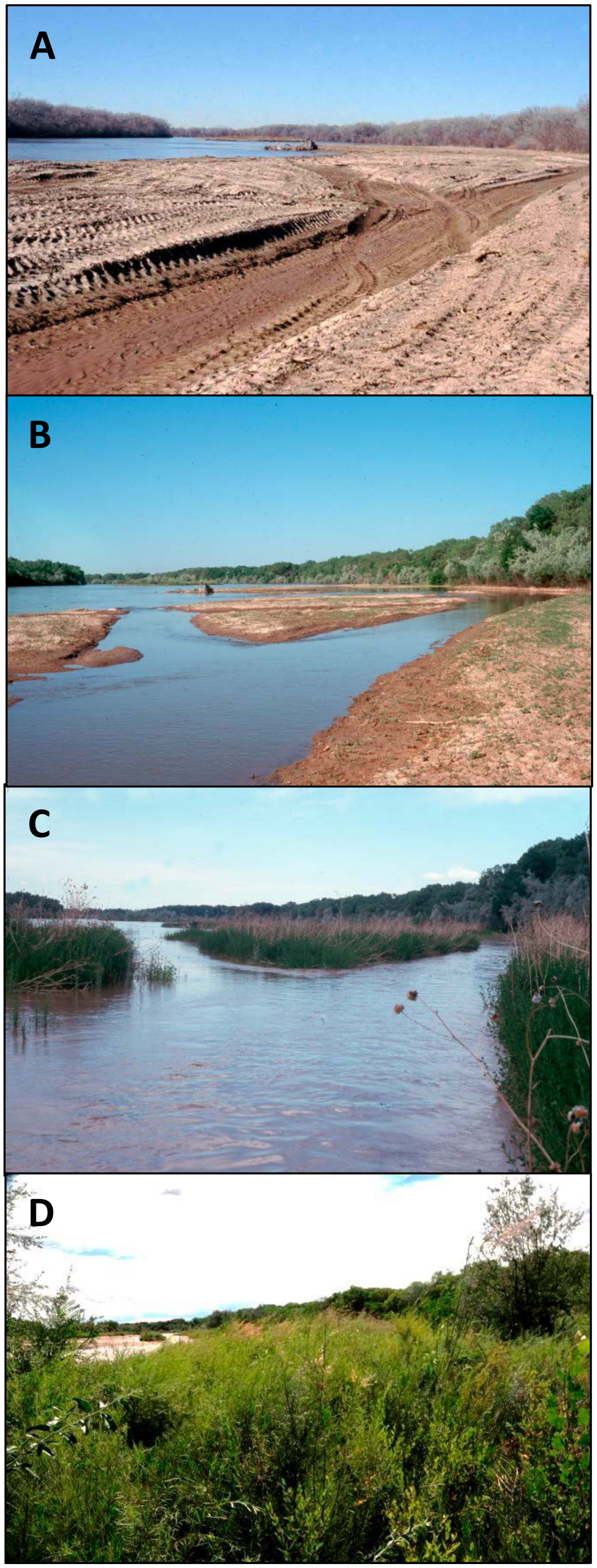

Figure 2. A) Mechanical manipulation on the AOP site prior to flooding where the bar area adjacent to the river was lowered 0.6 m and channels and bars excavated; B) first flooding event in spring 1998; C) early successional vegetation on constructed islands during spring 1999 flooding; D) by 2013, much of the original geomorphic surfaces are obscured by dense willow and cottonwood vegetation.

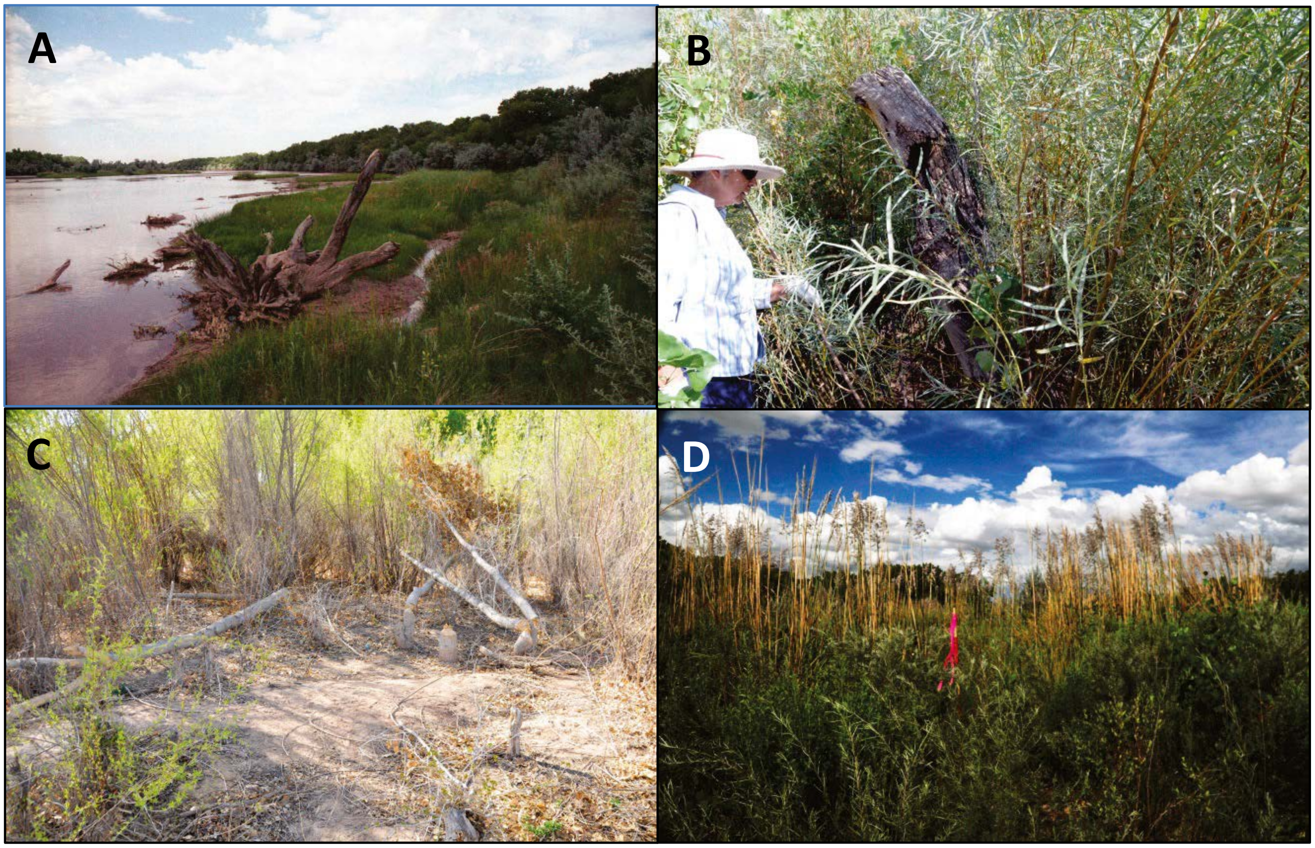

Figure 3. Restoration surprises. Even single large pieces of woody debris can provide sediment anchor points for the development of new bar environments (A). These sites can lead to the rapid development of new stands of cottonwoods and willows (B). While beavers can provide important ecosystem engineering functions where they build dams, here they have a clear impact through browsing on the development of mature cottonwood stands (C). Incursions of novel, highly invasive, and robust herbaceous species such as *Saccharum ravennae* (ravennagrass) can threaten restoration efforts (D).

and Follstad Shah et al. (2007). Further, we explore the implications for lowland, large-river restoration in the western U.S. and elsewhere, particularly where a modicum of natural hydrological regime elements are still extant that can provide opportunities for success with potentially lower costs in this age of limited resources.

Methods

Study Site

The AOP site is located on the lower end of a point bar in an urban reach of the Middle Rio Grande through the city of Albuquerque in central New Mexico (106°40′0.847″ W; 35°2′38.682″ N), that is part of the Middle Rio Grande Project, owned and co-managed by the Middle Rio Grande Conservancy District (irrigation district), the city, and the Bureau of Reclamation (see Figure 1). The river at this location had a shifting, sandy bed at approximately 2 m below the bank edge. The restoration site was approximately 2.5 ha and averaged 50 m in width along a channel length of about 400 m. Based on pre-treatment transect data, the site was dominated by dense stands of *Elaeagnus* shrub and small trees with scattered *Morus alba* (white mulberry), *Ulmus pumila* (Siberian elm), and *Tamarix chinensis* (five-stamen tamarisk) with a total of 72% canopy cover and a basal area of about 175 m^2/ha. The understory was dominated by grasses and sedges approaching 75% cover along with scattered forbs (Supplementary Table 1). The site lay adjacent to old-growth cottonwood gallery forest dominated by *P. deltoides* var. *wislizenii* forming a dense canopy (60% cover) with an equally dense sub-canopy of non-native trees (*M. alba*, *U. pumila*, *Ailanthus altissima* [tree of heaven], and *Elaeagnus*) and only scattered grasses and forbs in the understory (Supplementary Table 1B).

Climatically, the AOP site is located in a semi-arid zone where annual precipitation ranges from 83.5 mm to 403 mm with a mean of 219 mm (Albuquerque International Airport, NM US station 290234). While precipitation varied widely during the project period (Supplementary Figure 3), key events were the above-normal summer amounts at the initiation of the project in 1998 and 1999 followed by exceptionally low amounts in 2000, 2003, and 2011 (the latter three part of a region-wide extreme drought).

Hydrologically, river flows were determined by regulated discharges from Cochiti Dam (50 km upstream) plus municipal drinking water and agriculture diversions. During the project period, river discharges were moderate in 1998 and 1999 with peak releases occurring in late spring following snowmelt that were only about 10% above normal for the post-dam period (per Albuquerque gauge station 8330000, 6.5 km upstream from the site; Supplementary Figure 2). These were followed by relatively steady summer base flows (average of 25 CMS [850 CFS] from July through September), but, beginning in 2001, spring and summer releases began a downward trend in response to regional drought conditions that continued through 2003 (flows were 50–75% of the post-dam average). After 2004, yearly spring runoff increased again, but summer base flows remained low through 2013 (25% of the post-dam average). During the course of the project, actual flooding of the site was assessed qualitatively on site for extent and residence times during high flow events (> 85 CMS; 3,000 CFS).

Treatment

In winter 1997–98, the *Elaeagnus* stand on the site was mechanically removed by root plowing and the woody materials taken off site (Figure 2). A portion of the cleared bar was lowered sufficiently to allow overbank flooding during typical spring dam releases in the range of 85 to 140 CMS (3,000 to 5,000 CFS; Lowered Bar Zone, see Figure 1). Side channels and small islands were engineered in the lowered bar to slow flood waters, aid sediment deposition, and bring water to interior areas of the floodplain to create further complexity. Adjacent to and downstream of the lowered bar, an artificial bar at the same height was created using removed material from the lowered bar (Bar Fill Zone). A portion of cleared bar at the upper end was not lowered, and hence not subject to overbank flooding during the course of the project (High Bar Zone). In addition, where possible we left dead large woody debris (a few stumps and snags) along with any living cottonwoods and willows. The total amount of material moved was approximately 6,100 m^3 (8,000 yds^3). All work was performed in dry weather and without entering the active channel. The cost was of approximately $12,350/ha ($5,000/acre in 1998) for equipment and labor.

Following the mechanical treatment, limited re-sprouting of *Elaeagnus* and other invasives occurred. In 2003 and 2005, trained crews conducted spot cutting and herbicide treatments to control their regrowth or re-establishment (see Herbicide Treatment Details in Supporting Information).

Sampling and Analysis

Prior to treatment, we established four 30 m transects in the treatment area, each with 10, 1 × 1 m quadrats at 3 m spacing. Woody species aerial cover by species plus total grass and forb cover were visually estimated in each quadrat plus the number of shrub individuals and stems counted by size classes (Supplementary Table 1). Additional control data was provided by two monitoring plots established adjacent to the treatment site and sampled between 1998 and 2002 (Supplementary Table 2). One was located in the mature cottonwood forest on a slightly higher terrace to the north approximately 200 m; the other in a *Elaeagnus* stand on the bar approximately 200 m northeast of the treatment site. Each plot consisted of four parallel transects with eight quadrats each in which cover of all species was estimated and woody species individuals and stems counted by size classes (See Milford and Muldavin [2004] for details). None of the control samples were flooded over the course of the project.

For long-term monitoring purposes, we established a high-accuracy (± 5 cm), professionally surveyed random-systematic grid of 128, 12.5 × 12.5 m grid cells oriented in the cardinal directions and tied to an established benchmark (High Bar Zone, n = 28; Lowered Bar Zone, n = 58; Bar Fill Zone, n = 42; see Figure 1) immediately after the manipulation. The SW corner of each grid cell was monumented with rebar and 1 × 1 m quadrats established for measuring tree recruitment along with vegetation composition and abundance. In 1998 and 1999, we recorded counts of all tree regeneration on the quadrats by two-inch diameter classes along with average height by class. Starting in 2000, tree counts were expanded to a full census in the 12.5 × 12.5 m grid cells. Also starting in 2000, the cover of all plant species within the quadrats was estimated to the nearest half percent. Annual sampling continued through 2002 and then switched to five- to six-year intervals for 2007 and 2013. In 2013, we also evaluated trees for condition, live or dead, and signs of herbicide treatment or beaver herbivory. By 2013, the number of quadrats was reduced to 107 due to bank erosion (High Bar Zone, n = 28; Lowered Bar Zone, n = 45; Bar Fill Zone, n = 34).

As part of a related sister study on aerial insects, vegetation structure, and bird habitat, we established two additional vegetation monitoring sites in the New Bar Zone in stands created by sediment captured behind a large snag below the manipulated bar (Milford et al. 2009). Because of the narrowness of the stands, 1 × 1 m quadrats were placed at 5 m intervals in a three by five-line grid system with 17 quadrats in each stand and a total of 34 sample points within the New Bar Zone. These were measured annually from 2003–05 and again in 2013.

We sampled from mid to late summer. In 1998 and 1999 there were multiple sampling dates each year, but from 2000 onward sampling occurred only once during the growing season. Voucher specimens were collected for all but the most common species, identified, and deposited in the University of New Mexico (UNM) Herbarium. Scientific naming conventions follow the USDA PLANTS

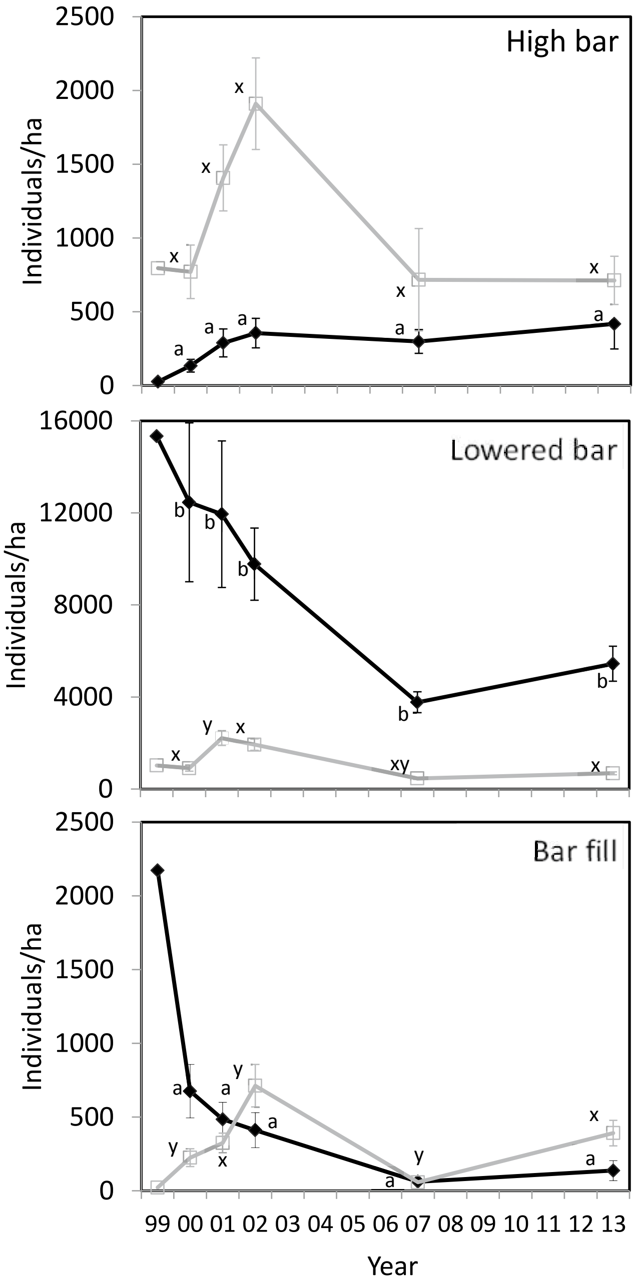

Figure 4. Since the second growing season (1999) following manipulation, densities of native riparian trees (mostly *P. deltoides* var. *wislizenii*, some *S. gooddingii*), and introduced species (mostly *Elaeagnus* and some *M. alba* and *U. pumila*) differed significantly across zones and between native (black lines) and introduced (gray lines) species through time within zones based on repeated measures ANOVA ($p < 0.05$) (note: Y-axis scale differs for bar lowered). Significant differences across zones are indicated by different letters (A, B natives; X, Y, or Z introduced species) based on Tukey's HSD post hoc means test. Within zones, native versus introduced species densities were significantly different ($p < 0.05$) except where SEs overlap (High Bar Zone n = 28; Lowered Bar Zone n = 58; Bar Fill Zone n = 42).

database (plants.usda.gov). All data were entered into an MS Access database and are available upon request.

For analysis, we grouped sample points (quadrats) by treatment zones: High Bar Zone, Lowered Bar Zone, and Bar Fill Zone (the New Bar Zone was excluded because of the lack of comparable sampling periods). Using Proc GLM in SAS (SAS v. 9, SAS Institute, Cary, NC), we conducted repeated measures ANOVAs of density and cover changes across zones stratified by origin (native versus introduced species) with a Mauchly's Sphericity Test (SAS 2010). In the case of sphericity violations, the Huynh-Feldt Epsilon (H-F) adjustment was applied to p-values. We followed with Tukey's Studentized Range (HSD) post hoc tests of individual mean differences.

Results

Flooding and Geomorphology

Based on our on-site observations, overbank flooding across the Lowered Bar and Bar Fill Zones occurred between 1998 and 2013, but the High Bar terrace was never flooded. The first flood occurred from late May into early June 1998, with the peak discharge exceeding 113 CMS (4,000 CFS). This represented a typical spring discharge for the Middle Rio Grande (see Supplementary Figure 2). The initial flooding lasted about 10 days and inundated all of the constructed channel areas and lowered bar surfaces (Figure 2B). The site flooded again in 1999 on several occasions from late May into late June. By then, vegetation cover was already high enough to help stabilize the site and modify floodwater dispersal (Figure 2C). Overbank flooding occurred again in 2001, 2005, 2008, 2009, and 2010 leading to slow filling of the on-site channels, buildup of the island bars, and dense vegetation (Figure 2D).

Erosion was also a factor. The first flood event (1998) removed a constructed island and a portion of the main constructed channel at the upper end of the site. There was also ongoing erosion along the entire bank that was accelerated during the 2001 flood, but since then bank erosion has been limited. In contrast, as material was being removed, sediment deposition occurred at the distal end of the site behind large woody debris piles (Figure 3A and B), creating new sites for vegetation establishment (the New Bar Zone).

Tree Establishment and Growth

With the initial overbank flooding of May 1998, there was a large *Populus* germination event and by the end of the growing season in 1999 there were more than 10,000/ha of established trees versus < 1,000/ha in the pre-treatment conditions (Supplementary Table 1). However, establishment patterns differed significantly across the bar zones (Figure 4). Densities in the Lowered Bar Zone were nearly seven times that of the Bar Fill Zone, and little or no establishment had occurred in the High Bar Zone, which was not flooded. The highest densities occurred in and along the constructed channels and, to a moderate degree, on the islands between the channels. The lowest densities were in areas of mechanically deposited bar-fill materials. In subsequent years, densities declined and by 2007 only 25% of the trees remained on the Lowered Bar Zone and 5% in the Bar Fill Zone (based on 1999 numbers; recruitment after 1999 was limited and not thought to be significant). There were limited increases in the High Bar Zone that occurred mostly in saturated areas. In 2013, there was a small uptick in numbers in areas that had been flooded in the intervening years, but there was no direct sampling in that period to confirm the year of establishment (limited age sampling of saplings indicated that some establishments had occurred between 2007 and 2013). Also beginning in 2003, a new cohort of trees became established in the New Bar Zone on sand deposits that formed behind large woody debris (1,128 trees/ha as of 2013).

Over the course of the study, introduced tree species densities were significantly lower than native trees in the Lowered Bar Zone compared to the High Bar and Bar Fill zones (Figure 4). The prevalence of non-natives in the High Bar Zone is attributed mostly to *Elaeagnus* recruitment and resprouting from remnant roots, and this may be the case in the other zones as well. *Elaeagnus* was the most abundant, but *Tamarix*, *M. alba*, and *U. pumila* were also present. Densities and sizes of individuals continued to increase through 2002 but were reduced in 2003 and 2005 by spot herbicide retreatments. Numbers have risen again since 2007, but at a slower rate, and in 2013 densities on the Lowered Bar and High Bar zones were still at only about 35% of their 2002 levels and 54% in the Bar Fill Zone.

Changes in stand structure of *Populus* across the site mirrored its overall density trends through time. The majority of the new establishments had reached the sapling stage of at least 1 m in height by year three (2000; Supplementary Figure 4). While overall numbers declined in the ensuing years through self-shading and beaver herbivory, the majority of the cohort continued to move into larger size classes. Ten years after establishment (2007), over 875 trees/ha were between 3 and 5 m tall. But by 2013, there was little or no recruitment into larger size classes. Instead, there was a renewed peak in the 1 to 2 m class, reflecting possible new establishments but also the impact of beaver herbivory. Nearly half of the established *Populus* but only about a third of the exotics (mostly *Elaeagnus*) were browsed by beaver (Supplementary Figure 5). Some *Populus* were killed outright, but many were resprouting from multiple stems at the base (most remained less than 2 m in height). Many larger trees were being felled, preventing the development of full-canopied woodlands (see Figure 3C).

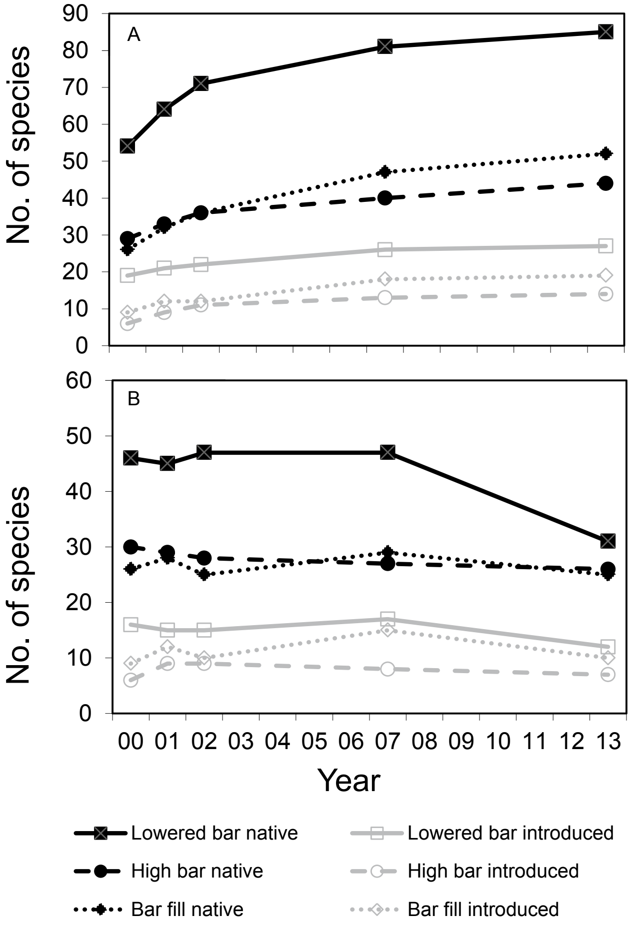

Figure 5. Cumulative (A) and yearly (B) species richness by zone and origin (native versus introduced). Natives outnumbered introduced plant species across zones and through time, particularly in the Lowered Bar Zone designed to receive overbank flood waters.

Vegetation Diversity

With a few exceptions, native species have dominated the site with respect to species richness and cover. While community composition has shifted through time, cumulative native species richness has only continued to increase. By 2013, a total of 103 native versus 35 introduced (non-native) species had been recorded, and through the years the percentage of native species has remained more or less constant at about 75% of the total species complement across all zones (Figure 5A, Supplementary Table 3). Overall, forbs accounted for about 50% of the species, followed by graminoids at 40%, and trees and shrubs making up the remainder. Native species richness was highest in the Lowered Bar Zone, with 40 or more species present in any given year (except the 2013 drought year) (Figure 5B). The other zones, while less rich, were still predominantly native in composition. In contrast, species richness in the adjacent untreated *Elaeagnus* control plot registered only 26 species (19 natives; 7 non-natives) over its five-year

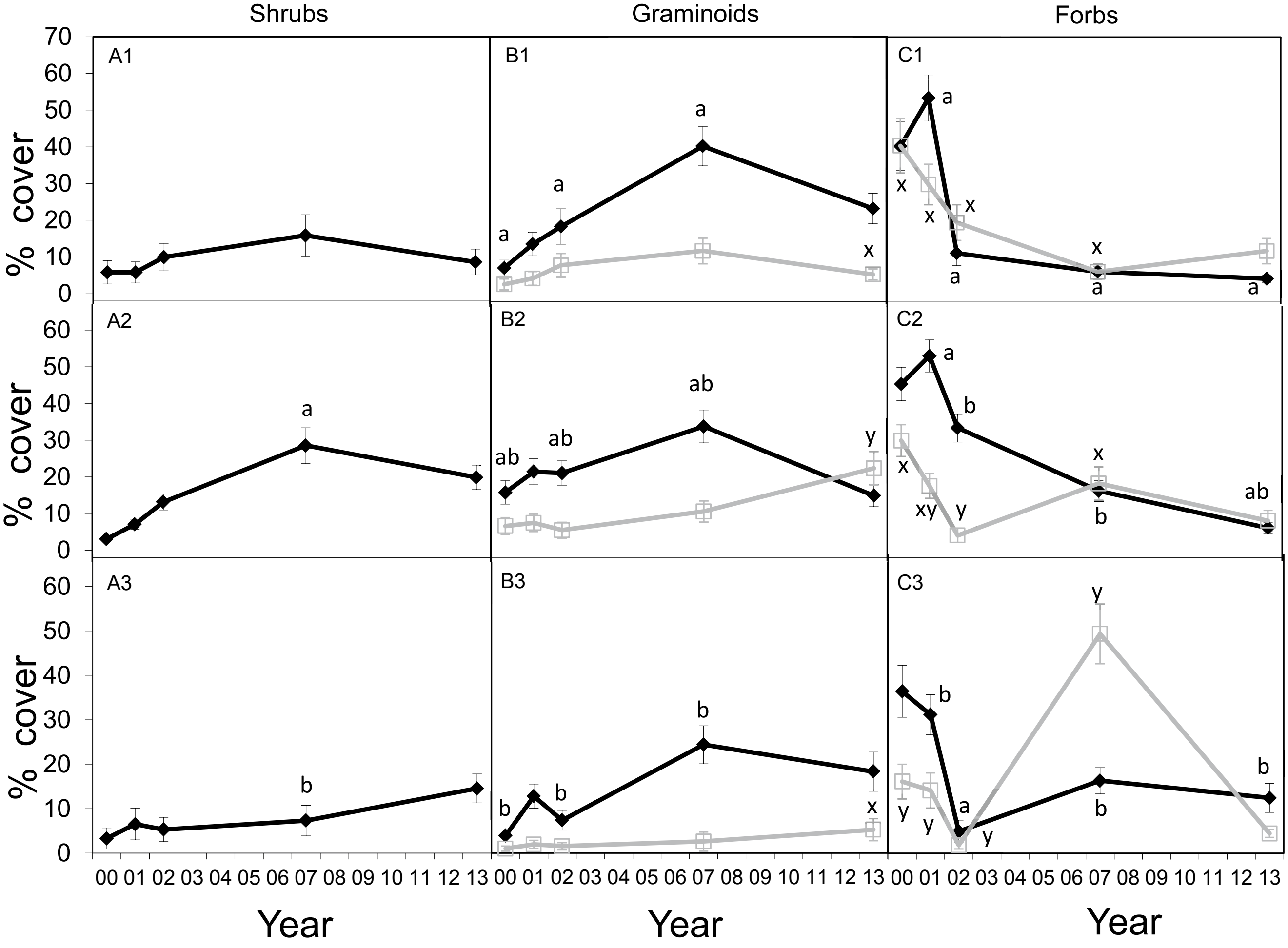

Figure 6. Percent canopy cover by life form (A = shrubs, B = graminoids, and C = forbs) differed significantly across zones (1 = High bar, 2 = Lowered bar, and 3 = Bar fill) and between native (black lines) and introduced species (gray lines) through time within zones based on repeated measures ANOVA ($p < 0.05$). Within years, significant differences across zones are indicated by different letters (A, B natives; X, Y, or Z introduced species) per Tukey's HSD post hoc test ($p < 0.05$). Within zones, native versus introduced species covers were significantly different ($p < 0.05$) except where SEs overlap.

record (1998–2002) and an average of 13 natives and five non-natives per year. The old growth cottonwood forest control plot was even more depauperate; it totaled only 10 species over the four-year period of record, five of which were non-native trees and shrubs.

Among shrubs, obligate and facultative wetland native species were the overwhelming dominants (Figure 6), led by *S. exigua* and *Baccharis salicina* (false willow). They were particularly prevalent in the Lowered Bar Zone (remembering that *Tamarix* and *Elaeagnus* were considered trees, not shrubs; Figure 6A2). Cover increased steadily, reaching a peak in 2007 and dipping in 2013. In the Bar Fill Zone, cover also increased as *S. exigua* clones expanded from the bar edge into the center of the zone (Figure 6A3).

A similar trend was seen among graminoids, with obligate and facultative wetland species such as *Carex emoryi* (Emory's sedge), *Schoenoplectus pungens* (common threesquare), *Distichlis spicata* (inland saltgrass), and *Panicum obtusum* (vine mesquite grass) dominant in the channels and islands of the Lowered Bar Zone (Figure 6B2). As might be expected, the sedges tended to be more prevalent in the channels than on the islands. Even in the usually depauperate Bar Fill Zone, grass cover, led by *D. spicata*, increased through time, approaching that of the other sites (Figure 6B3). Some introduced species also increased in cover and included *Agrostis gigantea* (redtop), *Sorghum halepense* (Johnsongrass), and *Cynodon dactylon* (bermudagrass)—species widely naturalized in riparian zones of the Southwest U.S. In contrast, *Saccharum ravennae* (ravennagrass), an aggressive noxious species, is a new incursion that appeared in 2007 as scattered individuals and then expanded to dominate the northern portion of the Lowered Bar Zone by 2013 (see Figure 3D).

Forbs were abundant in the early years in the High Bar and Lowered Bar Zones but dropped off significantly in cover by 2007 and 2013 (Figure 6C1 and 6C2). Native perennials in particular have declined since 2007, e.g., *Erigeron canadensis* (horseweed), *Euthamia occidentalis* (western goldenrod), and *Teucrium canadense* (Canada germander) declined 50–90% depending on location. Some species, such as *Equisetum laevigatum* (smooth horsetail)—a native facultative wetland species—increased in cover. Introduced perennials such as *Melilotus officinalis* (yellow sweetclover) and *Convolvulus arvensis* (field bindweed) were variable depending on year and sampling zone, but in general they also declined from 2007 onward.

Annuals, as might be expected, were even more variable. For example, *Helianthus petiolaris* (prairie sunflower) dominated several sites in 2001, but was found as only scattered individuals in 2007 and beyond. *Xanthium strumarium* (rough cocklebur) abundance peaked in 2002 but was nearly absent by 2007. *Ambrosia psilostachya* (common ragweed) was abundant in both 2001 and 2002 and was still common in the High Bar Zone in 2007, but uncommon elsewhere. *Bassia scoparia* (kochia) and *Salsola kali* subsp. *tragus* (prickly Russian thistle), both introduced annual species, reached peaks in cover in different places and times: 2002 on the High Bar Zone (15%), and 2007 in the Bar Fill Zone (31%), but were non-factors in other zones and years. In the New Bar Zone, introduced species were particularly low in cover, although herbaceous cover declined overall as tree and shrub cover increased (Supplementary Figure 6).

Discussion

Cottonwood Forest Development

After 16 years, cottonwoods, here represented by *P. deltoides* var. *wislizeni,* and other native woody species continue to dominate non-natives 3:1 and maintain high densities (7,000/ha) on a restoration site designed to take advantage of the remaining natural-process potential, particularly overbank flooding, in a highly regulated river system. This is in keeping with other studies, which show that given a sufficient flooding regime, cottonwood regeneration can be significant in western streams and rivers (Cooper et al. 1999, Rood et al. 2003, Bunting et al. 2013). Taylor et al. (2006), working 160 km to the south along the Rio Grande (Bosque de Apache National Wildlife Refuge) reported similar positive cottonwood recruitment responses to ours following the overbank flooding of a cleared tamarisk (*Tamarix* spp.) site but one that was not lowered (initially 19,100 seedling declining to 5,000/ha ten years later). Stromberg (1997) reports cottonwood reproduction densities of between 1,000 and 10,000/ha one year following natural flooding of un-manipulated sites on three unregulated rivers in Arizona, suggesting that our results tend to reflect outcomes that would occur under natural conditions. Furthermore, the continuing high density of cottonwoods is in stark contrast to the pre-treatment conditions on site with its scattered, mostly older, cottonwood poles (< 1,000 stems/ha) and in the adjacent old-growth forest and untreated *Elaeagnus* control sites where no cottonwood regeneration was occurring (Supplementary Tables 1 and 2), further arguing for the efficacy of the natural-process approach.

The site's physical heterogeneity led to differing residence times of flood waters on various surfaces which likely contributed to non-uniform tree and vegetation establishment. Slow drawdowns that generate moist soil conditions over a month or so are thought to be a critical element of successful cottonwood regeneration on flooded sites (Stromberg 1997, Taylor et al. 1999, Bhattacharjee et al. 2006). Also working in Bosque del Apache, Bhattacharjee et al. (2006), in a controlled experimental setting of differential drawdown rates following flooding of cleared sites, had seedling densities of 24,400/ha and 5,000/ha on slow and fast drawdown regimes respectively after one year. Taylor et al. (1999) noted that cottonwood regeneration was also highest along channels. On our site, the highest cottonwood densities were in the Lowered Bar Zone, particularly along the constructed channels and on the lower islands, areas with the longest floodwater residence time (two to three weeks as observed on site). Sites with low tree numbers still had high native phreatophyte shrub and herbaceous cover reflecting sufficient moisture availability (e.g., *S. exigua* and *D. spicata*).

In contrast, the Bar Fill Zone, composed of mechanically deposited sediments, remained problematic. Even after 16 years, the majority of this zone was still barren, although clonal willow shrublands have entered the zone from adjacent areas and tamarisk has become more prevalent here than elsewhere. Cottonwood seed source and availability should not have been an issue since healthy mature cottonwood forest lies directly adjacent to the site and for many kilometers up and down steam. While neither soil salinity nor groundwater availability appeared to be different compared to other zones (unpublished data), soil texture and stratigraphy may be. Cottonwood regeneration tends to be favored in fine-textured, moist soils (Cooper et al. 1999, Sher and Marshall 2003). Although more data is needed, the general depauperate nature of the fill zone may be a function of how fill materials were handled. That is, the general sediment mixing by large machinery may have increased the overall sand and silt component of soil at the surface and homogenized the soil column in a way detrimental to seedling germination and survivorship. Accordingly, more attention both experimentally and in practice needs to be given to mechanically mimicking how sediments are laid down by a river.

A surprise came in the New Bar Zone where sediment accumulated naturally behind large woody debris that was purposely left after the initial site clearing (Figure 3A). Herbaceous communities quickly became established followed by dense willow shrublands intermixed with cottonwood saplings established from seed (Figure 3B), and now tall (10 m+) cottonwood stands dominate these sites after only ten years (the trees in the New Bar Zone are taller than those on the older Lower Bar Zone). This was an unplanned outcome of the project, which bolsters the concept that having large woody debris available in large river systems is a key element for successful restoration (Abbe and Montgomery 1996, Gurnell et al. 2001, Montgomery and Piegay 2003), and supports the idea that the more natural the configuration in restoration efforts the better.

Most of the decline in cottonwood tree density can be attributed to self-thinning of dense stands and beaver herbivory. Beavers are endemic to the system, but because the river is now confined to a single channel rather than the historical braided, multichannel system, beavers no longer serve the same ecosystem engineering function of creating small dams on side channels that lead to backwater wetlands, ponds, etc. Rather, they are now primarily bank beavers living in dens along the river edge, foraging on the bars, and acting primarily as consumers with a significant impact on stand structure and the development of mature stands (Figure 3C). While additional measures, mechanical and otherwise, could be taken to protect trees, the key question is what the final density of mature cottonwoods in a stand should be and whether those target densities can be met despite the beaver browsing, particularly in regulated rivers (Breck et al. 2003). Provisional studies from mature 50 to 70-year-old forests in the reach estimate typical densities at between 200 and 400 stems/ha (Eichhorst et al. 2012), still below the current densities in the Lowered Bar Zone (800+/ha). Additional studies of stand structure and beaver herbivory rates are warranted to evaluate whether the cottonwoods will prevail as the restoration stands mature.

Both woody and herbaceous invasive species remain a chronic problem. *Elaeagnus* and other introduced woody plants were steadily increasing after the manipulation but at a slower rate than expected, and natives remained dominant with respect to number of species and abundance on all the sites except the un-flooded High Bar Zone. Because densities were relatively low, the retreatments in 2003/05 were an inexpensive intervention but the question is whether cottonwoods will out-compete the introduced species over the long term. With respect to saltcedar and cottonwoods, field studies by Sher et al. (2000, 2002), Sher and Marshall (2003), and Bunting et al. (2013) in the southwest U.S. indicate that cottonwood seedlings and saplings can maintain a competitive advantage, but Stromberg et al. (2007b) suggest that saltcedar may prevail where stream-flow regimes, including groundwater levels, are lower than optimal overall for cottonwoods and willows. At AOP, tamarisk densities are relatively low, which points towards cottonwood succeeding over the long term, but *Elaeagnus* remains a threat because it does not require flooding for successful germination and establishment, among other adaptations (Katz and Shafroth 2003, Reynolds and Copper 2010). The threat can lead to increased fuels and fire hazards that can undermine restoration efforts (Jemison 2003). Overall, AOP cottonwood numbers suggest that young stands have the potential to grow into a mature forest but to help ensure long-term success, low-cost exotic spot herbicide treatments should still be built into restoration plans.

The recent incursion of *S. ravennae* is a challenge not only on restoration sites but for general riparian management throughout the middle Rio Grande (Figure 3D). This is a tall and robust herbaceous species where classical herbicide treatments may not be appropriate because of the collateral damage to native herbaceous species. Hence, there is a strong need to explore alternatives before it becomes adventive throughout riparian ecosystems in the southwestern U.S.

Biodiversity Trends

Aside from establishing cottonwoods and willows, our results suggest that geomorphic manipulation and overbank flooding enhanced local plant biodiversity. The cumulative plant species richness of 114 species in the flooded zones was far higher than that found in the High Bar Zone (59 spp.) or in adjacent mature cottonwood forests and Russian olive control sites (10 and 26 species, respectively, Supplementary Table 2). In addition, Milford et al. (2009) report that treatment sites also enhanced animal diversity with insect biomass nearly double that of the control sites and the High Bar Zone along with increased abundance and richness of birds. This is most likely due to a combination of local patch diversity generated by the designed geomorphic complexity at the AOP site that created potentially differing local levels of groundwater connectivity for a range of species as well as differing residence times from the continued overbank flooding of the site. The high species richness and productivity indicates that merely clearing a site and following up with cottonwood pole planting without flooding will eliminate the majority of the biodiversity potential in a restoration effort.

On a community basis, the AOP site is developing into an intricate patch mosaic of young cottonwood stands, native shrub wetlands, wetlands, wet meadows, saltgrass meadows, and open ground. This composition and structural diversity was in striking contrast to the adjacent nearly uniform mature and low diversity cottonwood forest that dominates the river corridor (Supplementary Table 2; Milford and Muldavin 2004). This follows the recommendation of Weisberg et al. (2013) that riparian restoration look beyond just establishing trees to building a diversity of community types on a diverse fluvial geomorphic template. Furthermore, the flooded site has been persistently dominated by native trees, shrubs and forbs throughout the study period, suggesting that as succession proceeds and the site matures, natives will prevail.

Efficacy of This Natural-Process Riparian Restoration Project

Palmer et al. (2005) have proposed five criteria for evaluating ecologically successful river restoration: 1) a guiding image of the dynamic state (a dynamic, ecological endpoint identified); 2) improved ecosystems; 3) increased resilience; 4) no lasting harm; and 5) a completed ecological assessment. With respect to 1, the creation of a diverse patch mosaic met one of the key tenets of the Middle Rio Grande Biological Management Plan (Crawford et al. 1993), and was a guiding principal from the onset of this project. The project contributed to an improved ecosystem (2) at a local scale and has served as a model for subsequent larger projects. The early bank erosion could be seen as undermining the project and flooding may take out this site at some future date. Yet, erosion reflects a necessary component of reestablishing a dynamic patch mosaic and in this case was offset by the deposition of new sediments at the distal end of the site that led to the development of additional cottonwood stands—further reflecting an improved ecosystem under dynamic conditions. Has resilience been increased (3)? If greater biological diversity is assumed to impart resilience and stability (sensu Hooper et al. 2005), then the persistence of species-rich, native-dominated vegetation communities at AOP suggests the answer is yes. But new exotic threats such as *S. ravennae* and the impacts of altered beaver dynamics still put the site at risk. Lastly, *Elaeagnus* removal can temporarily impact animal habitats, but because this is mitigated by replacement with a greater diversity of native shrubs, grasses, and forbs providing forage and structure, no lasting harm was done (4).

With respect to the last criterion: is the ecological assessment complete (5)? Our results point to the value of long-term monitoring in understanding riparian dynamics as stated by Follstad Shah et al. (2007) and Bunting et al. (2013). Yet, it is still only a 16-year record and surprises like the invasion of *S. ravennae* and heightened beaver activity point to a need for continued monitoring and assessment. Furthermore, additional fauna and environmental monitoring would have been a plus for evaluating the efficacy of the project given the importance of restoration to the preservation of several sensitive bird and fish species in the Middle Rio Grande. But even within this research-oriented restoration project, in this age of limited resources there was and continues to be a significant challenge in obtaining funding for maintaining the monitoring grid. As Bernhardt et al. (2005) have stated, this is true for many river restoration projects across the nation and there is a need to be more strategic in assessments and cognizant of what the minimum requirements to assess success are. One strategy is to build citizen science initiatives to underpin the crucial elements of a monitoring protocol (Palmer et al. 2007). This may be particularly promising in the Middle Rio Grande where preservation and restoration of native cottonwood forest has become highly valued by the public (Weber and Stewart 2009), and where there is a well-established K–12 outdoor classroom program dedicated to riparian ecosystem monitoring of tree production, vegetation diversity, ground-dwelling arthropods, precipitation and groundwater at 32 sites along the Rio Grande (Eichhorst et al. 2012, Bosque Ecosystem Monitoring Program, bemp.org). In 2015, AOP was added to the BEMP network and we can look forward to following trends on the site well into the future.

Overall, AOP continues to provide insights on restoration possibilities using natural processes in a lowland arid river system where a modicum of residual habitat and sufficient hydrological conditions exist. While it represents only one case study, it is encouraging for the prospects of restoring many of the compositional, structural, and functional qualities of riverscapes on regulated large-river systems and tapping the potential for bringing, as Roseman and DeBruyne (2015) proposed, a "renaissance of ecosystem integrity in North American large rivers."

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Long-term Outcomes of Natural-process Riparian Restoration on a Regulated River Site: the Rio Grande Albuquerque Overbank Project after 16 Years.

Supplemental Material

Supplementary Table 1. Pre-treatment species absolute canopy cover plus number of individuals and basal area for trees based on 40 quadrats from 1998. Life form codes are 1 = trees, 2 = shrub, 3 = graminoid, and 4 = forb. Origin codes are I = introduced and N = native.

Life Form	Origin	Species name	Canopy cover	Individuals. /m^2	Basal area m^2/ha
1	I	Elaeagnus angustifolia	61.4	1.2875	12875
1	I	Ulmus pumila	5.1	0.0750	750
1	I	Morus alba	0.6	0.0500	500
1	N	Populus deltoides ssp. wislizeni	4.6	0.1250	1250
2	N	Salix exigua	0.3		
3	N	Sorghastrum nutans	0.4		
3	-	Other grasses	38.9		
3	N	Sedges	29.8		
4	N	Ambrosia psilostachya	0.5		
4	N	Apocynum cannabinum	0.1		
4	I	Convolvulus arvensis	2.7		
4	N	Conyza canadensis	0.1		
4	N	Equisetum laevigatum	1.4		

Supplementary Table 2. Absolute percent canopy cover by species for two control plots adjacent to the treatment site. Plot 98RB008 (A) was a Russian olive-dominated and established in 1998 to northeast of treatment site. Plot 98RB008 (B), was a mature cottonwood gallery forest plot to the north established in 1999 and sampled beginning in 1999. Life form codes are 1 = trees, 2 = shrub, 3 = graminoid, and 4 = forb. Origin is I = introduced and N = native.

A. Plot 98RB008

Life Form	**Origin**	**Species name**	**Year**				
			1998	**1999**	**2000**	**2001**	**2002**
1	I	Elaeagnus angustifolia	53.48	47.93	44.10	66.00	54.50
1	I	Morus alba	1.80	2.00	2.50	6.13	3.00
1	I	Ulmus pumila				0.40	0.23
1	N	Populus deltoides ssp. wislizeni		0.00	0.03	0.20	0.08
2	N	Baccharis salicifolia	2.00				
2	N	Salix exigua	2.10	2.20	0.15	2.14	1.15
3	I	Agrostis gigantea			0.50		
3	I	Cynodon dactylon	21.13	10.85	24.98	73.48	33.60
3	N	Distichlis spicata	0.53	1.50	1.88	6.38	2.50
3	N	Elymus canadensis			0.20	0.96	0.29
3	N	Muhlenbergia asperifolia	3.05	14.03	0.63	4.40	1.48
3	N	Sorghastrum nutans		1.88		0.10	0.10
3	N	Sporobolus airoides	5.25	3.15	0.15	5.30	2.40
3	N	Sporobolus compositus var. compositus	7.30	5.59	11.18	23.50	7.63
4	I	Convolvulus arvensis		0.05	0.13	0.53	0.20
4	I	Melilotus officinalis	0.44	1.06			
4	N	Ambrosia psilostachya	12.58	7.04	2.08	6.74	3.26
4	N	Apocynum cannabinum	1.63	0.80	0.33	0.25	0.18
4	N	Asclepias subverticillata	0.05	0.13	0.05	0.43	0.05
4	N	Equisetum laevigatum	0.08	0.03	0.02	0.23	0.17
4	N	Euthamia occidentalis		0.33			
4	N	Gaura mollis			0.03		
4	N	Helianthus annuus	0.14	0.08	0.03	0.13	
4	N	Lactuca tatarica var. pulchella				0.08	0.08
4	N	Symphyotrichum ericoides	4.68	5.36	6.30	18.25	8.65

B. Plot 99RB017

Life Form	**Origin**	**Species name**	**Year**			
			1999	**2000**	**2001**	**2002.00**
1	I	Ailanthus altissima	7.78	10.78	11.80	10.95
1	I	Elaeagnus angustifolia	19.93	24.75	23.78	21.03
1	I	Morus alba	2.38	0.03	2.63	2.50
1	I	Tamarix chinensis	2.30	4.88	2.58	2.58
1	I	Ulmus pumila	2.88	8.25	6.51	6.35
1	N	Populus deltoides ssp. wislizeni	51.88	59.13	62.13	62.25
1	N	Salix gooddingii		1.50	1.50	1.50
2	N	Amorpha fruticosa	0.38			
2	N	Parthenocissus vitacea	8.25	8.75	9.18	7.80
4	I	Convolvulus arvensis	0.10	0.05	0.35	0.25

Supplementary Table 3. Absolute percent canopy cover for all species found during for the course of the Albuquerque Overbank Project (AOP) study ordered by life form, origin and site zone (see text) with common names and symbol codes from the USDA Plants database. Origin cods are I = introduced and N = native.

Origin	Species name	Common name	Code	Zone	Year							
					2000	2001	2002	2003	2004	2005	2007	2013
Trees												
N	*Populus deltoides ssp. wislizeni*	Rio Grande cottonwood	PODEW	Bar Fill Zone	0.06	0.62	0.43				0.48	0.17
				Bar Lowered	6.28	7.26	10.61				19.08	11.21
				High Bar	12.67	13.26	7.89				20.00	21.97
				New Bar				2.32	3.64	7.04		52.82
N	Salix amygdaloides	peachleaf willow	SAAM2	Bar Lowered							0.00	
				New Bar						2.88		0.44
N	Salix gooddingii	Goodding's willow	SAGO	Bar Lowered	0.34	0.48	0.66				0.07	0.01
				New Bar				0.68	0.83	2.96		5.38
I	Ailanthus altissima	tree of heaven	AIAL	New Bar					0.01			
I	Elaeagnus angustifolia	Russian olive	ELAN	Bar Fill Zone	0.62	2.57	4.93					1.29
				Bar Lowered	2.75	5.23	9.64				2.09	10.59
				High Bar	6.81	9.26	19.81				4.44	5.88
I	Morus alba	white mulberry	MOAL	High Bar							0.37	0.19
				New Bar								0.01
I	Tamarix chinensis	saltcedar	TACH2	Bar Fill Zone	0.57	1.57	2.31				0.00	
				Bar Lowered	0.56	0.27	0.34				0.12	0.07
				New Bar				0.00	0.38	0.05		0.01
I	Ulmus pumila	Siberian elm	ULPU	Bar Fill Zone	0.05	0.69	0.17				0.26	3.05
				Bar Lowered	0.02	0.06	0.22				1.83	0.98
				High Bar		0.26	0.37					1.50
				New Bar				0.01				0.32
Shrubs												
N	Baccharis salicifolia	seepwillow	BASA4	Bar Fill Zone							0.07	
				Bar Lowered	0.25	0.15	0.74				4.76	9.15
				New Bar								0.09
N	Salix exigua	coyote willow	SAEX	Bar Fill Zone	3.21	6.33	5.05				6.36	11.74
				Bar Lowered	2.66	6.59	11.56				20.97	8.76
				High Bar	7.74	7.70	13.26				21.15	11.48
				New Bar				0.12	1.98	14.65		28.53
Graminoids												

N/I	Poa pratensis	Kentucky bluegrass	POPR	Bar Lowered		0.16	0.33				0.25	
						0.07						
N	Bolboschoenus maritimus ssp. paludosus	saltmarsh bulrush	BOMAP	New Bar						0.69		
N	Bouteloua barbata	sixweeks grama	BOBA2	Bar Fill Zone								0.03
N	Carex emoryi	Emory's sedge	CAEM2	Bar Fill Zone	0.12	0.85	0.24				0.12	0.05
				Bar Lowered	2.06	3.28	4.76				4.79	0.71
				High Bar	0.63	0.33	0.22				1.20	0.52
				New Bar				0.03		0.88		0.68
N	Cenchrus spinifex	sandbur	CESP4	Bar Fill Zone								0.05
				Bar Lowered		0.02	0.01					
N	Cyperus niger	black flatsedge	CYNI2	New Bar					0.00			
N	Cyperus odoratus	fragrant flatsedge	CYOD	Bar Fill Zone	0.11	0.35	0.13				0.12	
				Bar Lowered	0.38	0.07	0.14				0.03	
				High Bar		0.04						
				New Bar					3.38	0.03		
N	Cyperus squarrosus	bearded flatsedge	CYSQ	New Bar					0.05			
N	Distichlis spicata	inland saltgrass	DISP	Bar Fill Zone	1.02	3.43	2.06				12.71	5.54
				Bar Lowered	0.25	1.31	1.10				9.53	1.45
				High Bar	1.30	2.56	3.33				27.07	5.11
				New Bar								0.06
N	Eleocharis palustris	common spikerush	ELPA3	Bar Fill Zone	0.07							
				Bar Lowered	0.57	0.03	0.03					
				New Bar				11.47	4.28			
N	Elymus canadensis	Canada wildrye	ELCA4	Bar Fill Zone							0.05	
				Bar Lowered	0.03	0.24	0.94				0.87	0.46
				High Bar	0.22	0.37	0.26				0.19	0.11
				New Bar								0.00
N	Elymus elymoides	bottlebrush squirreltail	ELEL5	Bar Fill Zone							0.02	
				Bar Lowered	0.21		0.02					
N	Elymus x pseudorepens	false quackgrass	ELPS	Bar Lowered			0.12				0.10	0.02
				High Bar	0.22	0.30	1.96				2.19	0.07
N	Eragrostis pectinacea	tufted lovegrass	ERPE	Bar Fill Zone	0.07	1.65						
				Bar Lowered		0.05						

				New Bar					6.56	4.66		
N	Hordeum jubatum	foxtail barley	HOJU	Bar Fill Zone							0.39	
				Bar Lowered	0.03	0.30	0.02				0.21	0.03
				High Bar	0.56						0.06	
				New Bar				0.01				
N	Hordeum pusillum	little barley	HOPU	Bar Fill Zone							0.12	
N	Juncus arcticus var. balticus	Baltic rush	JUARB5	Bar Lowered			0.00				0.02	0.05
				High Bar							0.20	0.07
N	Juncus torreyi	Torrey's rush	JUTO	Bar Lowered	0.13	0.01						
				New Bar				0.39	0.00			
N	Leersia oryzoides	rice cutgrass	LEOR	Bar Lowered		0.57	0.05					
				New Bar				11.26	37.21	4.72		
N	Leptochloa fusca ssp. fascicularis	bearded sprangletop	LEFUF	Bar Fill Zone	0.05							0.11
				New Bar					1.83	0.06		
N	Muhlenbergia asperifolia	alkali muhly	MUAS	Bar Fill Zone	2.03	3.95	2.64					0.07
				Bar Lowered	1.99	3.02	3.58				1.89	0.66
				High Bar	1.70	3.96	5.78				2.41	3.54
				New Bar				0.26	0.03			
N	Muhlenbergia racemosa	marsh muhly	MURA	Bar Fill Zone	0.05	0.12						
N	Panicum capillare	witchgrass	PACA6	Bar Fill Zone	0.02		0.36				0.71	
				Bar Lowered	3.57	0.43	0.02				0.66	
				New Bar					4.03	0.90		
N	Panicum hallii	Hall's panicgrass	PAHA	Bar Lowered	0.02							
N	Panicum obtusum	vine mesquite	PAOB	Bar Fill Zone	0.05	0.48	0.17				1.74	6.69
				Bar Lowered	0.16	0.16	0.51				5.16	4.89
				High Bar	2.56	7.07	8.22				15.82	20.48
				New Bar					0.01	0.03		1.53
N	Pascopyrum smithii	western wheatgrass	PASM	Bar Lowered							0.74	
				High Bar							2.67	0.07
N	Paspalum distichum	knotgrass	PADI6	Bar Fill Zone	0.02	0.24	0.02					
				Bar Lowered	2.90	3.54	2.74				0.34	
				High Bar	1.37	1.85	0.37					
				New Bar				0.53	2.74	1.03		0.01
N	Phalaris arundinacea	reed canarygrass	PHAR3	Bar Lowered			0.74				1.64	

N	Poa arida	plains bluegrass	POAR3	High Bar			0.04					
N	Schoenoplectus pungens	common threesquare	SCPU10	Bar Fill Zone	0.02	0.03	0.06				0.05	
				Bar Lowered	0.73	3.40	1.19				0.39	0.00
				High Bar	0.26	0.19	0.15					0.02
				New Bar				0.34	2.59	0.58		
N	Schoenoplectus tabernaemontani	softstem bulrush	SCTA2	New Bar				0.18	0.44			
N	Sorghastrum nutans	Indiangrass	SONU2	Bar Fill Zone	0.07	0.48					0.05	0.36
				Bar Lowered	0.21	1.16	0.10				0.82	3.30
				High Bar	0.41	0.07	0.07					0.22
N	Sphenopholis obtusata	prairie wedgescale	SPOB	Bar Lowered							0.11	
N	Sporobolus airoides	alkali sacaton	SPAI	Bar Fill Zone		0.71	0.10					0.14
				Bar Lowered	0.05	0.13					0.33	0.20
				High Bar	0.00	0.19						
N	Sporobolus compositus	tall dropseed	SPCOC2	Bar Fill Zone	0.07	0.19	0.95					0.36
				Bar Lowered	0.30	0.66	2.77				0.03	0.62
				High Bar	0.09	0.22	0.81					
N	Sporobolus cryptandrus	sand dropseed	SPCR	Bar Fill Zone	0.04	0.01	0.28				5.37	1.85
				Bar Lowered	0.05	0.21	0.36				0.83	0.02
				High Bar			0.30				0.11	
				New Bar					0.04	0.06		
I	Agrostis gigantea	redtop	AGGI2	Bar Fill Zone	0.40	0.71						0.00
				Bar Lowered	0.44	1.02	0.56				4.74	0.74
				New Bar				2.74	0.38			
I	Bromus catharticus	rescuegrass	BRCA6	Bar Fill Zone							0.74	
				Bar Lowered	0.02	0.11	0.10				0.16	
I	Bromus japonicus	Japanese brome	BRJA	Bar Fill Zone								0.02
				Bar Lowered							0.10	
I	Bromus tectorum	cheatgrass	BRTE	Bar Fill Zone							0.17	
I	Cynodon dactylon	bermudagrass	CYDA	Bar Fill Zone		0.14	0.02				0.05	1.68
				Bar Lowered							1.23	1.64
				High Bar			1.37				5.56	1.13
				New Bar						0.09		
I	Echinochloa crus-galli	barnyardgrass	ECCR	Bar Fill Zone	0.02	0.30	0.07				0.02	
				Bar Lowered	1.46	0.74	0.03					
				High Bar							0.59	

				New Bar				0.35	17.88	1.61		
I	Festuca arundinacea	tall fescue	FEAR3	Bar Lowered	0.08		0.16				0.77	3.07
I	Hordeum murinum ssp. glaucum	smooth barley	HOMUG	New Bar				0.18	0.00			
I	Polypogon monspeliensis	annual rabbitsfoot grass	POMO5	Bar Fill Zone	0.17	0.05					0.02	
				Bar Lowered	0.18	0.33					0.02	
				New Bar				1.37				
I	Saccharum ravennae	ravennagrass	SARA3	Bar Lowered								10.80
				New Bar								0.16
I	Sorghum halepense	johnsongrass	SOHA	Bar Fill Zone	0.38	0.69	1.38				1.30	2.81
				Bar Lowered	3.39	4.15	3.80				1.98	2.09
				High Bar	3.56	5.67	8.78				8.63	5.97
<u>Forbs</u>												
N	Ambrosia acanthicarpa	flatspine burr ragweed	AMAC2	Bar Lowered	0.16	0.08						
N	Ambrosia psilostachya	Cuman ragweed	AMPS	Bar Fill Zone	3.22	6.24	2.23				0.05	0.06
				Bar Lowered	8.68	5.62	4.80				0.41	0.85
				High Bar	33.37	24.09	1.93				2.50	1.56
				New Bar					0.03			0.01
N	Apocynum cannabinum	Indianhemp	APCA	Bar Fill Zone							0.08	1.73
				Bar Lowered	0.28	0.93	1.10				3.37	1.44
				High Bar	0.11	0.11	0.15				0.19	1.52
N	Asclepias speciosa	showy milkweed	ASSP	Bar Lowered		0.02	0.03				0.33	0.03
				High Bar			0.04					0.43
N	Asclepias subverticillata	whorled milkweed	ASSU2	Bar Fill Zone		0.05						0.01
				Bar Lowered		0.02	0.03				0.03	0.14
				High Bar								0.00
N	Bidens cernua	nodding beggarstick	BICE	New Bar				0.38	0.06	0.09		
N	Bidens frondosa	devil's beggartick	BIFR	Bar Lowered	0.49	0.63	0.11				0.00	
				High Bar		0.37						
				New Bar				12.56	2.31	0.51		
N	Calibrachoa parviflora	seaside petunia	CAPA47	Bar Fill Zone		0.00						
				New Bar				0.04				
N	Centaurium arizonicum	Arizona centaury	CEAR12	Bar Lowered	0.16							
N	Chamaesyce serpyllifolia	thymeleaf sandmat	CHSE6	Bar Fill Zone	0.17	0.08	0.24				0.29	7.62

				Bar Lowered	0.93	0.13	0.53				0.01	0.01
				High Bar	0.11	0.33	0.15					
				New Bar					0.62	0.24		
N	Chenopodium incanum	mealy goosefoot	CHIN2	Bar Fill Zone							0.00	
N	Chloracantha spinosa	spiny chloracantha	CHSP11	High Bar	0.52	0.74	0.52				0.70	0.24
N	Conyza canadensis	Canadian horseweed	COCA5	Bar Fill Zone	0.96	3.61	0.10				1.38	
				Bar Lowered	0.63	5.50	0.31				0.22	
				High Bar	0.19	18.44	0.93				0.00	
				New Bar				0.12	0.01			
N	Descurainia pinnata	western tanseymustard	DEPI	Bar Fill Zone							1.64	
N	Dieteria canescens	hoary aster	MACA2	Bar Fill Zone		1.07	0.01				0.05	
				High Bar		1.70	0.48					
N	Dimorphocarpa wislizeni	spectacle pod	DIWI2	Bar Lowered	0.02							
N	Epilobium ciliatum	hairy willowherb	EPCI	New Bar				0.00				
N	Equisetum laevigatum	smooth horsetail	EQLA	Bar Lowered	0.38	0.29	0.59				1.96	0.19
				High Bar	0.10	0.12	0.12				0.41	0.24
				New Bar								0.00
N	Erigeron divergens	spreading fleabane	ERDI4	High Bar	0.04							
N	Erigeron philadelphicus	Philadelphia fleabane	ERPH	Bar Lowered	0.05							
N	Euthamia occidentalis	western goldenrod	EUOC4	Bar Fill Zone	5.37	7.21	0.22					0.12
				Bar Lowered	17.79	23.03	16.57				2.58	1.13
				High Bar	5.37	12.33	7.44				0.82	0.44
				New Bar				2.38	10.71	1.05		0.31
N	Gaura mollis	velvetweed	GAMO5	Bar Fill Zone			0.05				0.01	
				Bar Lowered	0.05		0.05				0.19	
				High Bar	0.15	2.48	0.04				0.06	
N	Glycyrrhiza lepidota	American licorice	GLLE3	High Bar								0.04
N	Grindelia squarrosa	curlycup gumweed	GRSQ	Bar Fill Zone		0.02						
				Bar Lowered	0.10	0.05	0.51				0.09	
N	Helianthus annuus	common sunflower	HEAN3	Bar Fill Zone							8.00	0.28
				Bar Lowered							1.11	
				High Bar							1.39	
N	Helianthus petiolaris	prairie sunflower	HEPE	Bar Fill Zone	23.61	8.90	0.02				0.12	

				Bar Lowered	5.32	0.63	0.03				0.15	0.00
				High Bar	9.54	8.44					0.71	0.00
N	Lactuca tatarica var. pulchella	blue lettuce	LATAP	Bar Fill Zone	0.10							0.07
				Bar Lowered	0.05	0.05	0.48				1.06	0.05
				High Bar			0.07				0.26	0.44
				New Bar				0.01				
N	Lycopus americanus	American bugleweed	LYAM	Bar Lowered		0.02	0.02					
				New Bar				0.00	0.02			
N	Mentha arvensis	wild mint	MEAR4	New Bar						0.01		
N	Mentzelia albicaulis	whitestem blazingstar	MEAL6	Bar Fill Zone							2.04	
				Bar Lowered							1.15	
N	Oenothera elata ssp. hirsutissima	Hooker's eveningprimrose	OEELH	Bar Fill Zone	0.71	1.19	0.02				0.07	
				Bar Lowered	0.00		0.94				0.58	
				High Bar	0.74						0.15	
N	Persicaria lapathifolia	curlytop knotweed	PELA22	Bar Lowered	0.38							
N	Physalis longifolia var. longifolia	longleaf groundcherry	PHLOL3	High Bar	0.02						0.11	
N	Portulaca oleracea	common purslane	POOL	Bar Fill Zone			0.01					0.14
N	Pseudognaphalium stramineum	cottonbatting cudweed	PSST7	Bar Fill Zone							0.00	
				Bar Lowered	0.16	0.03	0.17					
				New Bar					0.01	0.07		
N	Pyrrhopappus pauciflorus	smallflower desert-chicory	PYPA4	Bar Lowered			0.03				0.01	0.02
N	Ranunculus cymbalaria	alkali buttercup	RACY	New Bar				0.12				
N	Ratibida tagetes	green prairie coneflower	RATA	Bar Lowered			0.00					
N	Solanum elaeagnifolium	silverleaf nightshade	SOEL	Bar Fill Zone			0.01				0.43	0.10
				Bar Lowered							0.01	0.00
N	Solidago canadensis	Canada goldenrod	SOCA6	Bar Lowered	0.18	0.08	0.36					
N	Sphaeralcea incana	gray globemallow	SPIN2	High Bar								0.07
N	Symphyotrichum ericoides	heath aster	SYER	Bar Fill Zone	0.05	0.17	1.67					0.05
				Bar Lowered	1.79	2.13	1.97				0.12	0.52

				High Bar	0.81	0.96	1.22					0.26
N	Symphyotrichum lanceolatum ssp. hesperium	white panicle aster	SYLAH	Bar Fill Zone		0.10						
				Bar Lowered	1.00	0.51	1.15				0.18	0.06
				High Bar	0.30	0.74	1.74				0.59	0.21
				New Bar					0.38	0.03		
N	Teucrium canadense var. occidentale	western germander	TECAO	Bar Fill Zone								0.03
				Bar Lowered	1.07	1.00	0.67				0.90	1.04
				High Bar	0.04		0.15				0.04	
N	Typha domingensis	southern cattail	TYDO	Bar Lowered		0.08						
N				New Bar				1.21	4.06	3.81		
N	Verbena bracteata	bigbract verbena	VEBR	Bar Lowered	0.02	0.02					0.00	
				High Bar							0.04	
N	Veronica anagallis-aquatica	water speedwell	VEAN2	New Bar				0.91				
N	Xanthium strumarium	rough cocklebur	XAST	Bar Fill Zone	0.86	1.36	0.00					0.00
				Bar Lowered	3.72	7.93	0.19				0.02	
				High Bar		0.04						
				New Bar				0.65	4.85	11.03		0.37
I	Asparagus officinalis	garden asparagus	ASOF	Bar Lowered							0.03	0.00
I	Convolvulus arvensis	field bindweed	COAR4	Bar Fill Zone		0.05	0.36				4.49	1.77
				Bar Lowered	0.07	0.35	3.23				0.70	0.50
				High Bar	8.96	10.70	24.83				2.74	11.13
				New Bar					0.03			
I	Kochia scoparia	common kochia	BASC5	Bar Fill Zone							0.05	
				Bar Lowered	0.02							
				High Bar	2.59	11.19	0.39					
				New Bar						0.00		
I	Lactuca serriola	prickly lettuce	LASE	Bar Fill Zone							0.36	
				Bar Lowered		0.11	0.04				0.16	
				High Bar		0.04						
I	Medicago sativa	alfalfa	MESA	New Bar					0.06			
I	Melilotus officinalis	yellow sweetclover	MEOF	Bar Fill Zone	14.72	10.49	0.74				6.50	0.67
				Bar Lowered	27.54	15.61	0.07				15.10	6.59
				High Bar	41.39	5.89	0.03				4.56	4.62
				New Bar				1.63	0.06			

I	Plantago major	common plantain	PLMA2	Bar Lowered	0.33	0.13	0.28				0.00	0.02
				New Bar					0.04			
I	Polygonum persicaria	Lady's thumb	POPE3	New Bar					0.43	0.06		
I	Rumex stenophyllus	narrowleaf dock	RUST4	Bar Lowered	0.02	0.02	0.03				0.09	
I	Salsola tragus	prickly Russian thistle	SATR12	Bar Fill Zone	0.79	3.03	0.55				20.44	0.49
				Bar Lowered	0.00							
				High Bar	0.78	11.52	0.67				0.93	
I	Scorzonera laciniata	cutleaf vipergrass	SCLA6	Bar Fill Zone							0.02	
I	Sisymbrium altissumum	tall tumblemustard	SIAL2	Bar Fill Zone							11.00	
I	Sonchus asper	spiny sowthistle	SOAS	Bar Lowered	0.02	0.05	0.00				0.05	
				High Bar		0.00						
				New Bar						0.01		
I	Taraxacum officinale	common dandelion	TAOF	Bar Lowered	0.05	0.05	0.10					
I	Tribulus terrestris	puncturevine	TRTE	Bar Fill Zone		0.01	0.01					0.70
				High Bar			0.04					

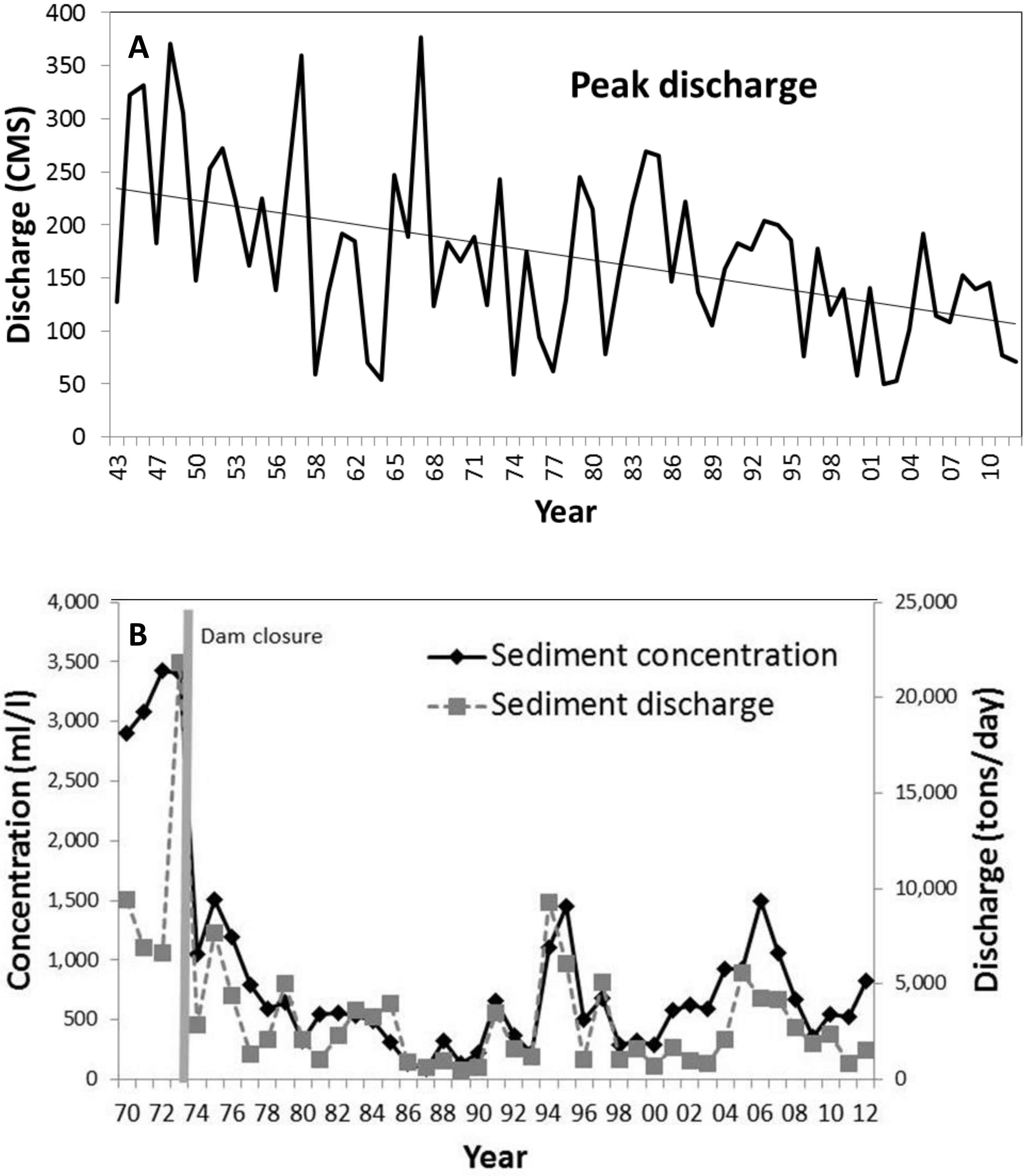
Herbicide Treatment Details

For the sprouts (an inch or two in diameter or smaller at ground level) of saltcedar, Russian olive, Siberian elm, we used a low-volume, oil basal method applied with a backpack sprayer. The formulation contains a 25 percent mixture of Remedy*
or Garlon 4* (Triclopyr). How to obtain a 25 percent mixture for the oil basal method: Add one part of Remedy or Garlon 4 formulation to three parts vegetable oil.

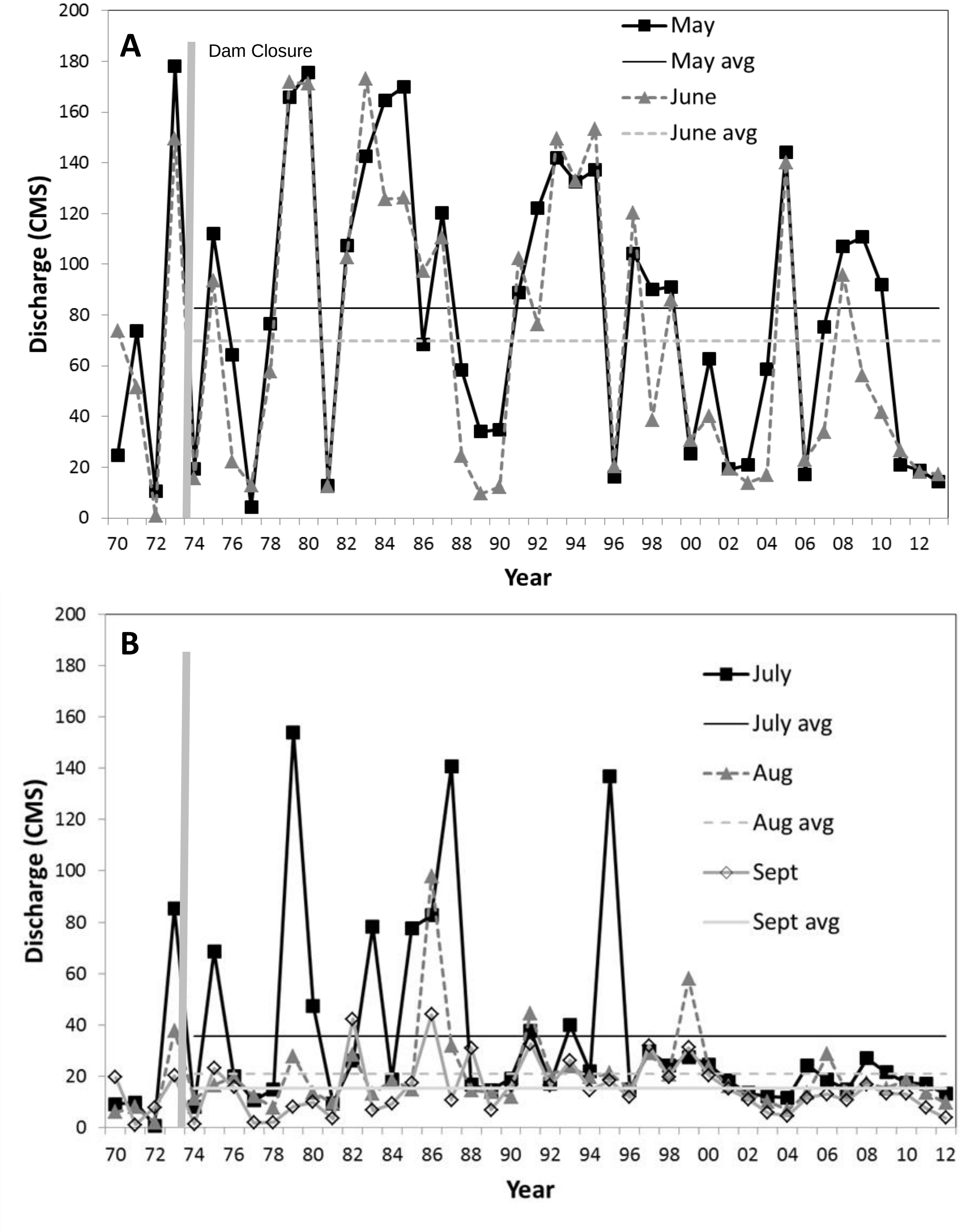
For the larger trunks we used a low-volume cut stump method to achieve "root kill." To obtain a 50 percent mixture for the cut stump method: add one part of Garlon 3A* to an equal part of water (you use a spray bottle to apply the herbicide directly onto the recently cut trunk (within a few minutes).

More information on these techniques can be found within the USDA Forest Service, SW Region, preliminary field guide, "Low-Impact, Selective Herbicide Application for Control of Exotic Trees in Riparian Areas: Saltcedar, Russian-Olive, and Siberian Elm" by Doug Parker and Max Williamson, May 2003.

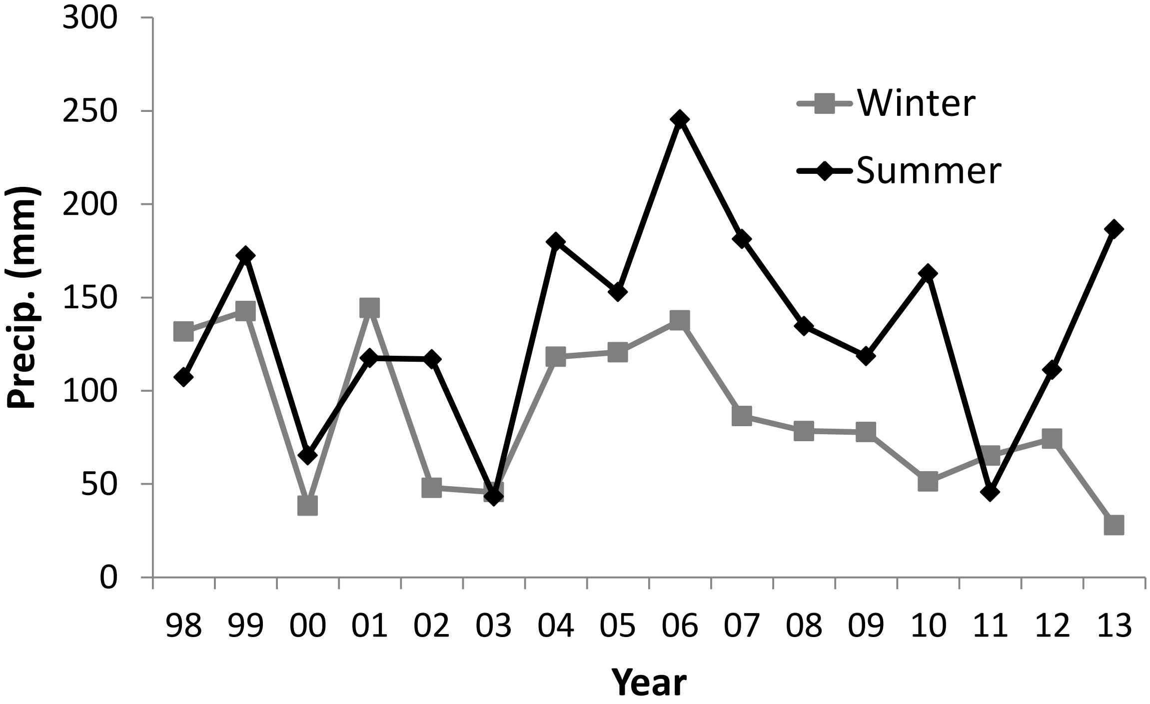
*Trademark of Dow AgroSciences



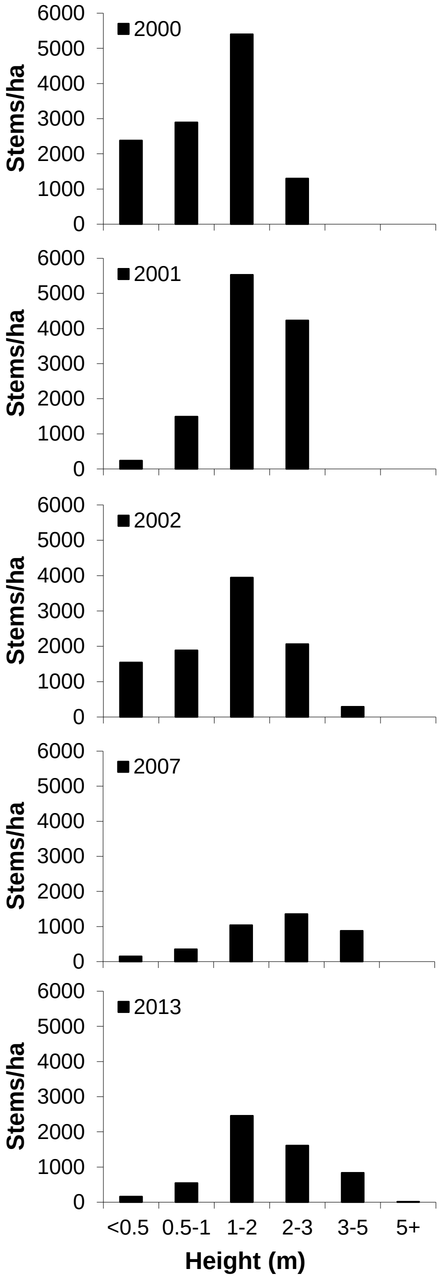
Supplementary Figure 1. A) Annual peak discharges from 1943 to present at the Albuquerque gauge station (8330000), approximately 5 km (2 mi) upstream from the AOP site. Cochiti Dam was completed and closed in 1973 and peak discharges have declined since (Y= -66.375x + 8363.1, $R^2 = 0.2195$); B) sediment concentration and discharge since 1970 show steep declines since dam closure.



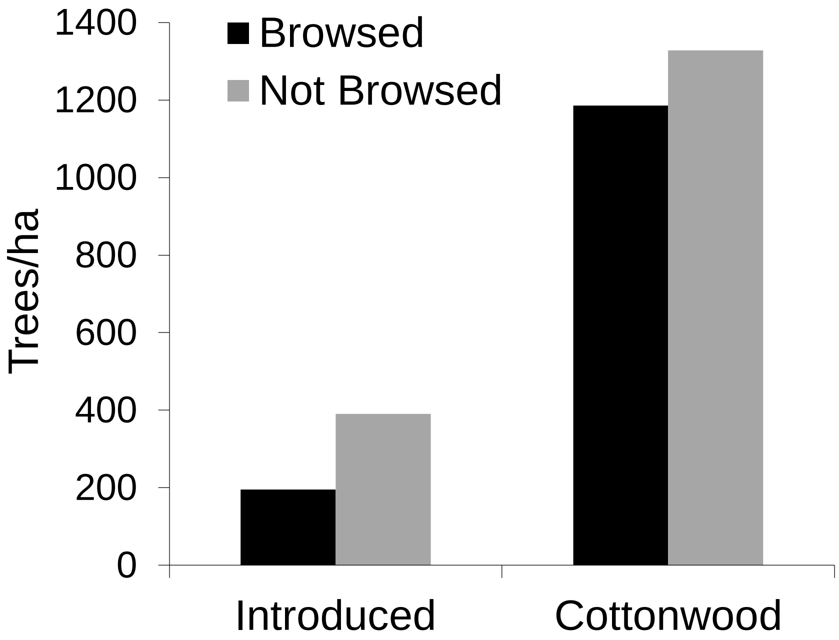
Supplementary Figure 2. A) Average monthly spring-snowmelt period discharges in the months of May and June from 1970 to present; B) Average monthly discharges for the summer months of July, August and September from 1970 to present where flows are augmented by local monsoon thunderstorms that can generate peak flows similar to that of the spring runoff period (Albuquerque gauge station (8330000). Cochiti Dam was closed in 1973.



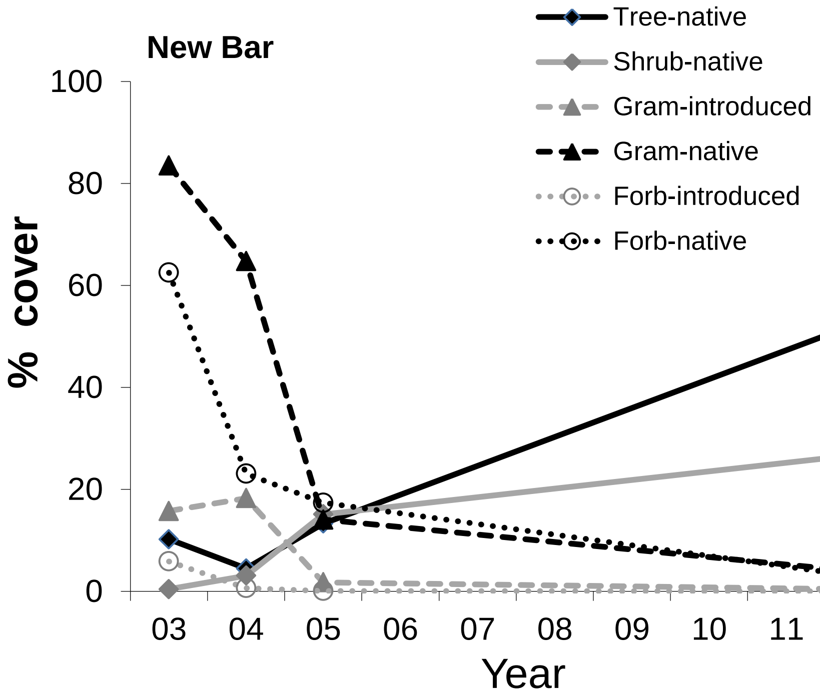
Supplementary Figure 3. Mean summer (April-September) and winter (October-March) water-year precipitation as measured at the Albuquerque International Airport during the project period.



Supplementary Figure 4. Cottonwood-stand structure based on a tree-height census that began in 2000, the fourth year of the Albuquerque Overbank Project. The number of trees making it to the tallest class in 2013 is less than expected and is primarily a function of beaver browsing returning many trees to the 1-2 m height class.



Supplementary Figure 5. Beaver herbivory was clearly impacting Rio Grande cottonwood and introduced species (Russian olive, saltcedar, and Siberian elm) as of 2013. While a species preference was not detected and plants tend to resprout, beavers are clearly impacting stand development.



Supplementary Figure 6. In the New Bar zone, herbaceous cover declined as the canopy cover for trees and shrubs increased, but introduced woody species such as Russian olive and saltcedar have not become established on the site over the first 10 years.