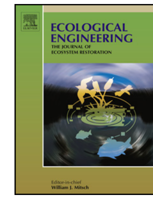
Ecological Engineering 70 (2014) 241–254

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Remote sensing analysis of riparian vegetation response to desert marsh restoration in the Mexican Highlands

Laura Norman[a,*], Miguel Villarreal[a], H. Ronald Pulliam[b], Robert Minckley[c], Leila Gass[a], Cindy Tolle[d], Michelle Coe[e]

[a] US Geological Survey, Western Geographic Science Center, 520N. Park Ave., Ste. #102K, Tucson, AZ 85719, United States
[b] Borderlands Restoration, L3C; P.O. Box 1239, Patagonia, AZ 85624, United States
[c] University of Rochester, Department of Biology, River Campus, Box 270211, Rochester, NY 14627-0211, United States
[d] Tutuaca Mountain School, 12134 Mountain Goat Lane, Custer, SD 57730, United States
[e] University of Arizona, School of Geography, Tucson, AZ 85719, United States

ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 16 April 2014
Accepted 18 May 2014
Available online 20 June 2014

Keywords:
Gabions
Cienega
Wetlands
Restoration
NDVI

ABSTRACT

Desert marshes, or cienegas, are extremely biodiverse habitats imperiled by anthropogenic demands for water and changing climates. Given their widespread loss and increased recognition, remarkably little is known about restoration techniques. In this study, we examine the effects of gabions (wire baskets filled with rocks used as dams) on vegetation in the Cienega San Bernardino, in the Arizona, Sonora portion of the US-Mexico border, using a remote-sensing analysis coupled with field data. The Normalized Difference Vegetation Index (NDVI), used here as a proxy for plant biomass, is compared at gabion and control sites over a 27-year period during the driest months (May/June). Over this period, green-up occurred at most sites where there were gabions and at a few of the control sites where gabions had not been constructed. When we statistically controlled for differences among sites in source area, stream order, elevation, and interannual winter rainfall, as well as comparisons of before and after the initiation of gabion construction, vegetation increased around gabions yet did not change (or decreased) where there were no gabions. We found that NDVI does not vary with precipitation inputs prior to construction of gabions but demonstrates a strong response to precipitation after the gabions are built. Field data describing plant cover, species richness, and species composition document increases from 2000 to 2012 and corroborate reestablished biomass at gabions. Our findings validate that gabions can be used to restore riparian vegetation and potentially ameliorate drought conditions in a desert cienega.

1. Introduction

Although wetlands represent a very small area of arid and semi-arid regions in North America, they contribute disproportionately to regional biodiversity because of their structural complexity and the surface water associated with them. Desert wetlands, called cienegas, occur where groundwater comes to the surface, usually fed by springs. Access to otherwise scarce surface water has resulted in a long and particularly close association between desert wetlands and humans. The largest pre-European settlements regularly burned them to plant crops and improve hunting (Davis et al., 2001). More recently, human impacts on wetlands have intensified as demands from livestock and on groundwater have risen to supply larger populations (Webb and Leake, 2006). If climate change predictions are realized, conservation challenges related to water management will be further exacerbated (Davies, 2010). There is a consensus that western North America will become hotter and drier in the near future (Seager et al., 2007), with some areas getting a more intense monsoon (Dominguez and Cañon, 2010). This leads to potentially more variable streamflow (Milly et al., 2008). As such, assessing different restoration approaches of wetland and riparian areas in arid and semi-arid regions for effectiveness is timely and important (Heller and Zavaleta, 2009; Gibbs, 2000).

The Mexican Highlands subarea, part of the Basin and Range physiographic province, extends about 275 km along the US-Mexico border (Woodard and Durall, 1996). A large percent of this overlaps with the Madrean Archipelago or Sky Island region, where unparalleled biodiversity exists (Omernik, 1987; Warshall,

* Corresponding author. Tel.: +1 5206705510.
E-mail address: lnorman@usgs.gov (L. Norman).

http://dx.doi.org/10.1016/j.ecoleng.2014.05.012

1995; Skroch and Matt, 2008; Spector, 2002; Fig. 1). The broad valleys (basins) separated by steeply rising mountains (ranges) result in multiple independent hydrologic systems. Although predominately classified as "desert", this region is also known for its vegetation diversity, high-elevation forests and diverse freshwater ecosystems, many of which are remnants from when the area was wetter (Papoulias, 1997). In the early 1900s, overgrazing and prolonged drought resulted in near full appropriation of surface water in these aridlands, leaving augmentation dependent on groundwater supplies (Turner et al., 2003). The drawdown of groundwater has resulted in reduced stream- and spring-flow and a reduction in riparian habitat in the 21st century (Webb and Leake, 2006).

Precipitation in the Mexican Highland/Madrean Archipelago is strongly influenced by the North American Monsoon. During this late-summer period, short, intense rain events deliver more than half of the area's annual precipitation (Loik et al., 2004) and these sparse but high-intensity rainfall events generate overland flow and surface runoff that can lead to erosion of poorly-vegetated landscape. Arroyos are ephemeral creekbeds carved into the floodplain when erratic overland flow occurs (Betancourt et al., 1993). Arroyos drain river-bed marshes and change the natural flora and fauna by widening and deepening the channel (Schumm and Hadley, 1957; Vogt, 2003). When surface runoff is high, little recharge infiltrates to the basin aquifer, and high-intensity flow transports heavy sediment loads to channels, which contributes to nonpoint source pollution in surface water bodies. In wild lands, sediment is the primary pollutant in streams (Branson et al., 1981). Negative effects of accelerated erosion and sedimentation on water quality and on long-term site productivity have been well-documented in this region (Lopes and Ffolliott, 1992; Marsh, 1968).

Federal agencies, including the US Forest Service, National Park Service, Fish and Wildlife Service, Bureau of Land Management, and Department of Defense are major land managers in the US portion of the Mexican Highlands, endeavoring to sustain natural resources and engage in best management practices (Norman et al., 2008; Quijada-Mascareñas et al., 2012). Additionally, private ranch owners have identified the need to restore and maintain natural processes for diverse populations in the future (McDonald, 1995; Curtin, 2002; Sayre, 2005). One approach to conserve water from episodic rains is to install check dams, gabions, and trincheras. Trincheras, the Spanish word for trenches, are loose-rock structures, like riprap or one-rock dams that are used to line and stabilize channels and hillsides first developed by ancient cultures. Entire hillsides terraced by trincheras exist in the Mexican Highland region, with the earliest date of 1000 B.C. from just south at Cerro Juanaquena, Chihuahua (Herold, 1965; Anyon and Leblanc, 1985; Fish et al., 2013).

In this study, we examine the effects of structures similar to trincheras on vegetation in a riparian habitat of the Chihuahuan Desert. Wire-enclosed rock structures, or gabions, were placed in a channelized streambed to reduce water flow, and prevent and repair arroyo-cutting in a dryland cienega. A gabion is a stationary grouping of rocks encased in wire mesh, and like check dams, are used to slow water and reduce erosion in streams (Waterfall, 2004). These infrastructure detain water, sediment and debris, thus slowing runoff and allowing for infiltration and recharge. Sediment deposition raises the bed level behind the gabion, and is thought to facilitate the establishment of riparian vegetation. Gabion emplacement and vegetation are predicted to establish a positive feedback loop where vegetation will further reduce flow velocity and flooding, decrease erosion, and increase sediment deposition (Wischmeier and Smith, 1978). As a result, subsurface water recharge could be enhanced by gabions because of greater soil moisture storage capacity and infiltration rates of captured sediments (Kamber Engineering, 1990).

The efficacy of water control structures for rangeland restoration in the western U.S. is unclear. Hadley and McQueen (1961) showed that downstream from diversion structures on rangelands in Wyoming, peak flow was reduced and that sediments loads were diminished by up to 75%s. Peterson and Hadley (1960) surveyed nearly 200 erosion control structures on semiarid rangelands in the Upper Gila River basin, at the southern Arizona-New Mexico border, and found that vegetation did not change around these structures. Although they did not report the number of control structures that had breached, they concluded that expensive maintenance limits this practice. However, their study was conducted during and immediately after the most severe drought in the last century. Peterson and Branson (1962) evaluated Civilian Conservation Corps treatments from the 1930s, including earthen dams, spreaders, and rock check dams, finding that more than half of the structures had breached within a few years after construction but otherwise, vegetation cover was improved. Miller et al. (1969) concluded that water spreader structures in the western United States positively impacted vegetation if precipitation is more than 280 mm per year and have little or no effect on vegetation where annual precipitation is less than 203 mm. Baker et al. (1999) document positive results of restoration efforts from 1934 in the main channel the San Simon Valley cienega, Arizona, which included diversion dikes, spreaders, detention dams, gully plugs and seeding; they conclude that while side-channel structures are perceived as largely ineffective for restoration, they prevent further headcutting and reduce water velocities. Norman et al. (2010) modeled the use of gabions for reduced peak flows in Nogales, Sonora, Mexico, and Gass et al. (2013) found no impact of these on vegetation response. No studies have evaluated how gabions influence vegetation green up for desert marshland recovery.

Our research assesses vegetation changes around sites where gabions have been installed to restore a desert cienega on both sides of the US-Mexico border. Cienegas or desert marshlands are particularly rare habitats that support an estimated 19% of endangered, threatened and candidate species in this region (Minckley et al., 2013). We hypothesized that rock gabion structures would be related to increased water availability and soil moisture capacity resulting in a detectable green-up response in nearby vegetation. We used remote sensing data, which are commonly used to monitor ecological changes over large scales related to management activities (Mas, 1999; Pettorelli et al., 2005). Multispectral data have been used successfully to map and monitor riparian vegetation in arid environments (Nagler et al., 2001; Johansen and Stuart, 2006; Villarreal et al., 2012). Jones et al. (2008) evaluated changes in the pattern of greenness of riparian areas using satellite imagery in an area protected from grazing and development since 1988, and in a relatively unprotected area. They found that the protected area was greener and had larger, more continuous patches of positive change. Henshaw et al. (2013) demonstrated the capacity of remotely sensed data to enhance our understanding of interactions between fluvial processes and riparian vegetation, specifically using Landsat TM satellite data covering the last 30 years. Their study demonstrated these data provide a wealth of information that could support further biogeomorphological investigations in other large rivers.

To analyze changes in riparian vegetation related to watershed restoration efforts in the Mexican Highlands, we calculated the Normalized Difference Vegetation Index (NDVI) from a series of multitemporal Landsat Thematic Mapper (TM) images and sampled NDVI at areas with gabions. Comparisons were made before and after installation and also in relationship to areas randomly selected (controls) to isolate and quantify changes in vegetation greenness specifically resulting from gabion installation. We then

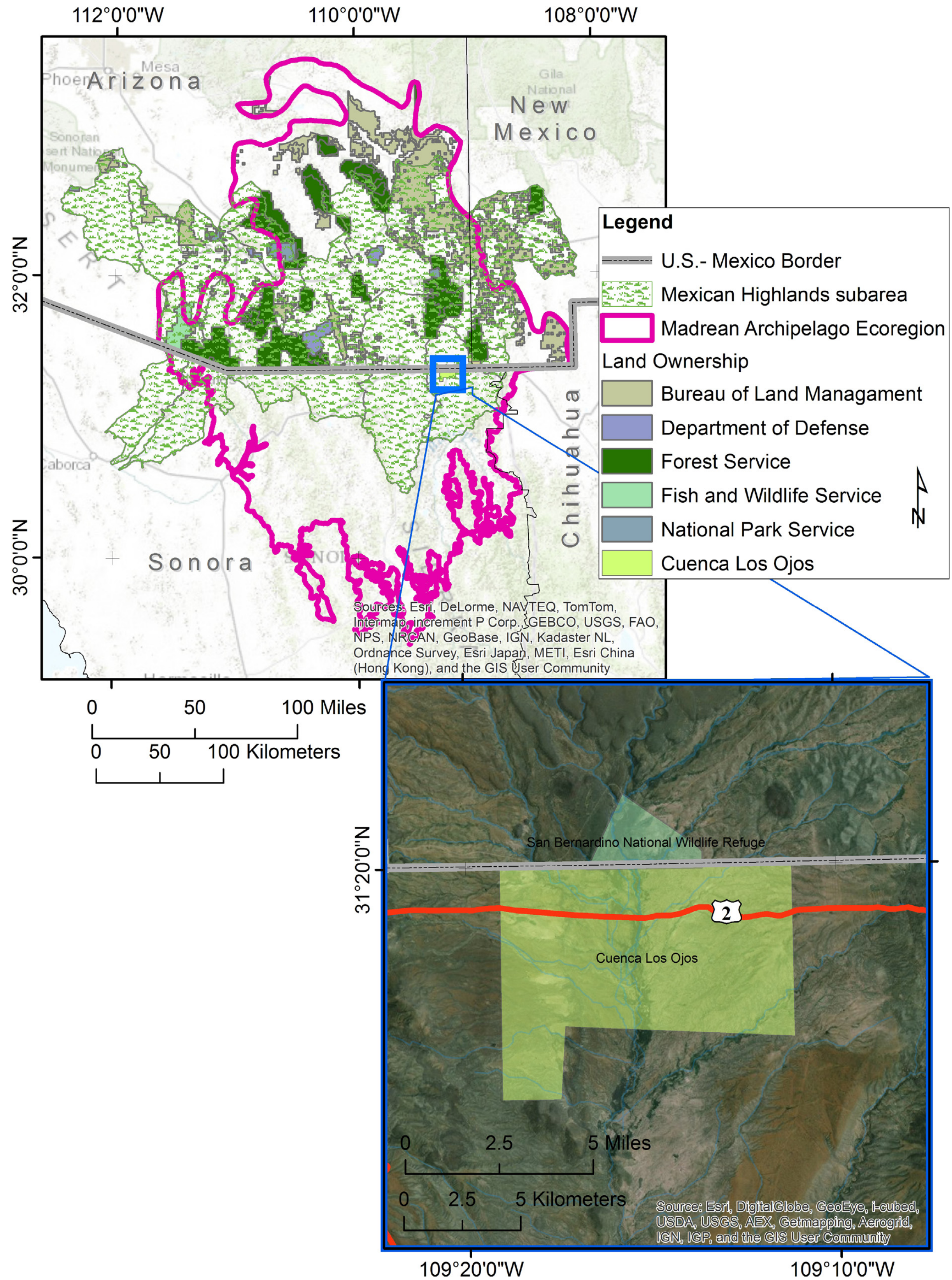


Fig. 1. The Mexican Highlands boundary and watersheds, in relationship to the Madrean Archipelago (modified from U.S. Environmental Protection Agency, 2010). Inset shows the study area, San Bernardino National Wildlife Refuge, Arizona, USA and Cuenca Los Ojos, Sonora, Mexico.

corroborate these patterns with vegetation surveys and repeat photography to provide further details about the changes in plant species composition and cover associated with restoration activities. The binational watershed evaluated is the San Bernardino Valley of Sonora, Mexico, and Arizona, USA, where gabions have been installed for riparian restoration (Fig. 1).

2. Methods

2.1. Study area

The San Bernardino River is one headwater of the Rio Yaqui, the largest river system in northwest Mexico. The Rio Yaqui drains the western side of the Sierra Madre Occidental and enters the Gulf of California at Los Mochis, Sinaloa. The desert cienega that is the focus of this study, hereafter referred to as Cienega San Bernardino, is associated with a spring complex. Cienegas, unlike most marshlands that form in closed depressions, develop along streams and join more familiar riparian communities (e.g., gallery forest/scrubland) where perennial water intersects the surface in channels sufficiently stable for biological succession to proceed. Cienega stabilization results either (1) where a channel is blocked by coarse, flood-carried sediments deposited *en masse* due to sudden flow dissipation by abrupt channel widening or infiltration, or dammed by debris flows carried in by a highly erosive tributary (Cooley et al., 1966), or (2) where impervious strata that resist downcutting crosses a channel, and forces groundwater to surface. Cienegas persist if near enough to the headwaters for low probability of scour. Elsewhere, given sufficient time to develop, they may become large enough to resist all but the largest flood (Hendrickson and Minckley, 1985). C_{14} and pollen dates for deposits indicate cienega habitat persists for >3000 years (Martin, 1963; Martin et al., 1961), and sediments from Cienega San Bernardino indicate it has been intact for >5000 years (Minckley and Brunelle, 2007).

Mature cienega habitats are structurally less complex and are dominated by a different plant community than occurs in riparian habitats along desert rivers and streams (Hendrickson and Minckley, 1985). Once formed, soils of cienega habitats are permanently saturated, with reducing chemical conditions that prevent colonization by any but specialized plants (*e.g.*, low-growing sedges, rushes and grasses). Trees are scarce, limited to taxa like willows (*Salix* spp.) that tolerate saturated soils. Adjacent soils may become salinized by capillarity and evapotranspiration, thus vegetated only by halophytes. Historically, cienegas acted as long-lasting, self-protecting, groundwater-storage reservoirs, regulating downstream hydrographs (Hendrickson and Minckley, 1985). Protracted seepage from their large storage capacities stabilized base flow, so discharge below was more permanent and less variable. Due to greater roughness in densely vegetated channels, velocity of floodwater slowed and attenuated, resulting in lowered discharge peaks and more deposition and retention, than erosion, of sediments.

Historical loss of cienegas, including Cienega San Bernardino, is related to overgrazing. Most of western North America was severely grazed, in some areas for 300 years, and this overstocking with cattle (Haskett, 1935; Wagoner, 1952, 1960) was accompanied by severe erosion in the 1800s. Grassland deteriorated, desert scrub expanded and wetlands and their biota declined (Bahre, 1991; Humphrey, 1987; Turner et al., 2003). Arroyo cutting then lowered water tables to new base levels near arroyo bottoms (Antevs, 1952; Bryan, 1925; Cooke and Reeves, 1975; Hastings, 1959), depriving wetland and riparian plant communities of subsurface water, critical for survival. After arroyo cutting dried the Cienega San Bernardino, the former wetland was converted mostly to irrigated agriculture. At present, wetted cienega surface is limited to areas close to and downstream of springs (Malcolm et al., 2005); and represents less than 2% of the area that was present pre-channelization (R. Minckley pers. obs.)

Fig. 2. Photo taken in 2002 of gabions at Cienega San Bernardino, in Sonora, Mexico, "shows two gabions: one at the bottom left, and one at the center top. They work together to slow the flow of run-off water and to catch silt." (CLO, 2014).

Cienega San Bernardino spans the US-Mexico border and restoration activities on the US part began earlier than occurred on the Mexican part. In 1979, The Nature Conservancy bought the US parcel, passing it to United States Fish and Wildlife Service in 1982 (U.S. Fish and Wildlife Service, 1979) to establish the San Bernardino National Wildlife Refuge (SBNWR). Habitat improvement started in 1982 with the removal of cattle. Undesired woody plants were eliminated or thinned, weeds mowed and burned to favor native grasses and abandoned fields and uplands were reseeded. Desired woody plants were replanted, and gabions were installed to reduce erosion and stabilize arroyos. The first gabion constructed on the SBNWR was in 1984, with nineteen to follow. Malcolm and Radke (2008) used a Before-After-Control-Impact (BACI) study to compare changes in the SBNWR, of bird density, avian species richness, and community composition across 3 years (one pre-restoration and two post-restoration). They found that the passive restoration starting in 1980 has resulted in the establishment of a riparian gallery that had not existed prior. The active restoration did not result in new tree establishment, but they consider sedimentation assists in establishing new annual vegetation and resultant free standing water (Malcolm and Radke, 2008).

In 2000, the Cuenca Los Ojos (CLO) Foundation acquired a ranch that included the Cienega San Bernardino and other properties adjoining SBNWR in Sonora, Mexico. Restoration like that already occurring on SBNWR began immediately, along with new fencing and facility renovation and construction. Construction of gabions on CLO began in 2001 and continues today (Fig. 2). In 2013, 46 loose-rock wire gabions and one big check dam are located on CLO. The basin behind the 90 m wide check dam, completed in 2008, has filled with 6 m of sediment at the spillway. Research using terrestrial and airborne LiDAR and remote sensing, coupled with hydrological modeling, field observation, and stream-flow sensors is being done to assess the impacts of restoration efforts on sediment and hydrology at CLO (DeLong and Henderson, 2012; Henderson and DeLong, 2012; Jemison et al., 2012). Pulliam (2012) is integrating field surveys of bees, birds, and plant species to document reestablishment of historic wetland plant and animal communities finding increases in stream flow, riparian vegetation, cienega acreage, and vertebrate populations.

Table 1
Table displaying the site designation and water drainage of the four sites on CLO, with vegetation censuses from 2000, and the species richness of perennial aquatic, terrestrial and exotic plants in each. Abbreviations in the site column stand for two different drainages where sites were located, Rio San Bernardino (RSB) and Hay Hollow (HH).

Site	Drainage	Aquatic	Terrestrial	Exotic
Riparian Site 1 (RS-1)	RSB	3	8	2
Riparian Site 2 (RS-2)	RSB	2	6	2
Riparian Site 3 (RS-3)	HH	0	6	2
Riparian Site 4 (RS-4)	HH	0	5	2

2.2. Experimental design

Forty-six gabions at CLO and 20 gabions at SBNWR were plotted as points along stream channels in the study area. Gabion points were buffered by 300 m circles, resulting in 16 areas of interest with minimal overlap for analysis (Fig. 3). Circle buffers were then adjusted by intersecting with 60 m wide riparian stream areas to develop buffer strips. These were created to approximate the potential area of influence the gabions might have on the riparian zone at each of the test locations that could be monitored from satellite.

We also mapped 16 random (control) strips on streams outside of a 1 km area from where gabions were concentrated, to ensure gabions were not impacting the vegetation that far away. Points were randomly distributed along the stream lines, and circles converted to buffers strips as described for the treated sites – these were added to the analysis to account for control sites (Fig. 4).

2.3. Data collection

2.3.1. Satellite imagery

Multispectral Landsat Thematic Mapper (TM) images (30 m) for the years 1984–2011 were selected to consider what the conditions of vegetation were before and after on the streams where gabions or check dams have been installed, and to compare with locations nearby that had no restoration done. We obtained one cloud-free scene a year ($n = 27$) from either May or June (a generally dry period) for each study location. Images were atmospherically corrected using the ATCOR module in ERDAS Imagine and converted from 8-bit Digital Numbers (DNs) to surface reflectance.

2.3.2. Field surveys

Vegetation on four sites were surveyed in riparian habitat on CLO in Cienega San Bernardino in 2000, 6–9 months after grazing ended at CLO (Minckley, 2013). Riparian habitat was considered to be in waterways where cottonwood trees (*Populus fremontii*), Goodding's black willow (*Salix gooddingii*) and western hackberry (*Celtis reticulata*) were established; tree species that are phreatophyes typically associated with permanent surface water (Brown, 1994). Two sites along Rio San Bernardino (RSB) had surface water present year-round and two sites on Hay Hollow (HH) had surface water through most of the winter but not usually in the summer months unless there had been recent rain (Table 1 and Fig. 5).

Vegetation was sampled using four, 50 m long linear transects that crossed the channel at the midpoint of each transect. To limit the survey so that desert vegetation growing above the channel was not included, the ends of the transect were restricted to the bottom of the channel and the edges, and did not extend to the top of the channel bank. All individuals intercepted along transects were counted, measured at the base, and identified to species richness of perennial aquatic, terrestrial and exotic plants in each.

2.3.3. Watershed components

To account for potential differences in the streams being analyzed, we employed some measures to account for differences in the number of contributing tributaries and contributing source area. We assigned a numeric stream order (SO) to links in the San Bernardino Watershed stream network using the Strahler (1957). This is based on the number of upstream tributaries and the SO increases when streams of the same order intersect. At each buffer strip used in the analysis, the contributing source area (CSA) was calculated from the centroid of the polygon. This was done using 10-m Digital Elevation Models (DEMs) in ArcMap and delineating the point's watershed boundary (effectively identifying each point as its own outlet). CSA and stream order calculations for buffer strip were documented for analysis.

2.3.4. Precipitation

The SBNWR has maintained two precipitation gauges, on the west side (Shop) and the east side (Hay Hollow Wash) of the refuge since 2005, and the closest long-term site to the San Bernardino Valley is 35 km east at Douglas-Bisbee International Airport. We used the long-term dataset from the Douglas-Bisbee International Airport in this study because the precipitation data for the SBNWR weather stations (2005–2012) were less than the duration of this study and was closely correlated with the matching 8-year record from Douglas-Bisbee International Airport station (Spearman's rho 0.876).

2.4. Analysis

2.4.1. Normalized difference vegetation index (NDVI) analysis

The Normalized Difference Vegetation Index (NDVI) was used to analyze each of the satellite images. NDVI is calculated as a ratio of reflectance in the near infrared (NIR) and red spectral bands:

$$\mathrm{NDVI} = \frac{\text{NIR band} - \text{Red band}}{\text{NIR band} + \text{Red band}}$$

NDVI values range from −1 to +1, but absence of green vegetation typically yields values near zero. Thus, zero means no vegetation and close to +1 indicates the highest possible density of green vegetation. We extracted the mean NDVI values (for each year) for all 30 m pixels contained in the buffer strips (treated and control), using the ArcMap Zonal Statistics and Model-builder tools, to compare values. This allowed us to track changes in vegetation greenness around the gabions and control points over time.

2.4.2. Statistical analysis

Generalized linear models (GLM) were used to estimate the effects of precipitation and the presence or absence of gabions when NDVI changes were detected. The data were divided into four groups, contrasting sites with and without gabions *and* before and after gabion construction. The first gabion was constructed on CLO in 2001; however, most were constructed between 2002 and 2004. We therefore categorized the NDVI values into the following four groups (G): (1) gabion sites before construction (1984–2003); (2) gabion sites after construction (2004–2011); (3) random sites before construction (1984–2003) and (4) random sites after construction (2004–2011).

All statistical analysis was performed in the R programming language. Two analyses were done. The first general model was represented in R as:

$$\mathrm{GLM}\left(\mathrm{NDVI}{\sim}\frac{G}{1+\mathrm{precip}} - 1\right)\pi$$

where G represents the four levels of the treatment factor, and precipitation from February to May (precip) is treated as co-factor. This

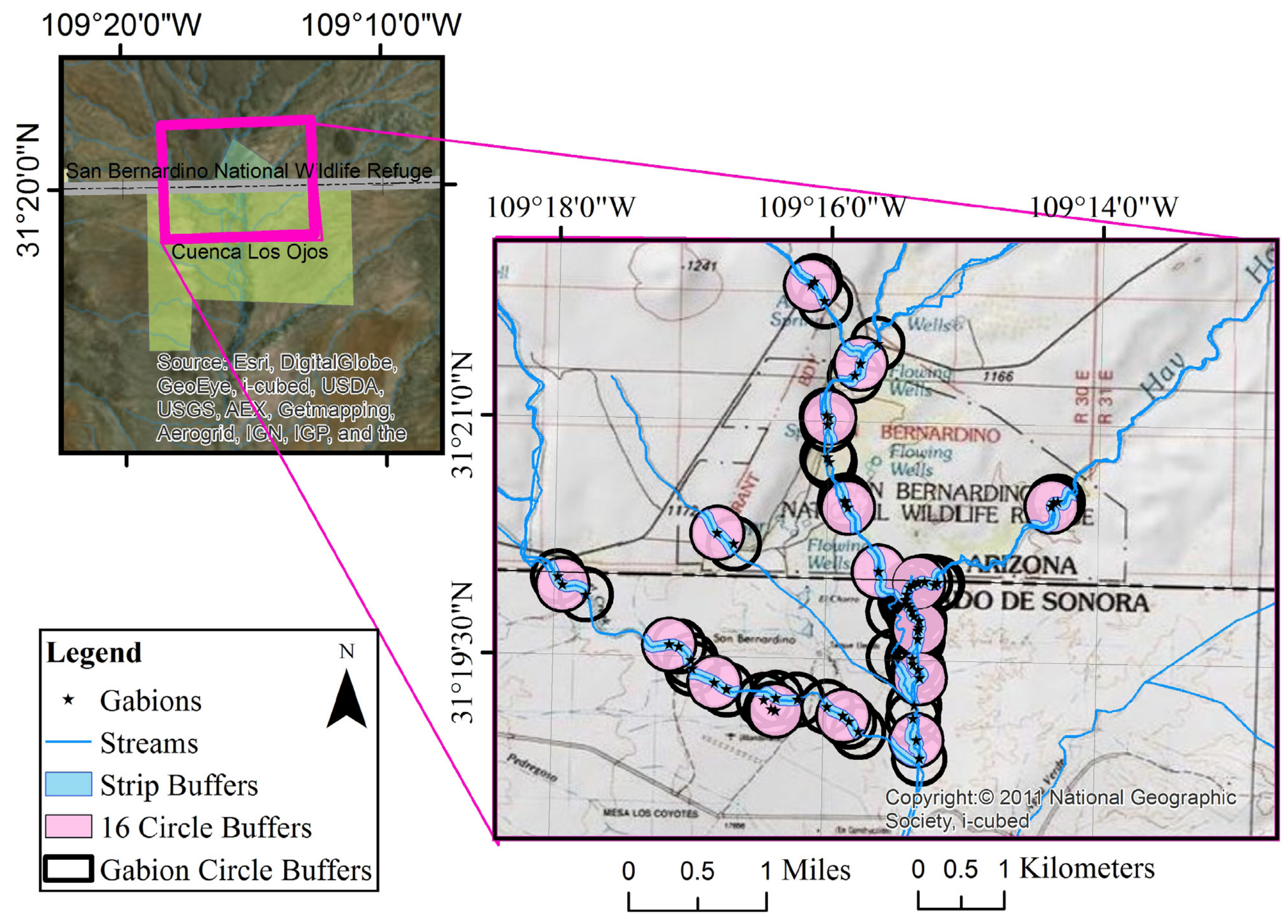


Fig. 3. Graphic depicting the 66 gabion point locations, gabion circle buffers, selected 16 circle buffers, and final riparian strip buffers created for analysis of treated sites in the Cienega San Bernardino.

form of the regression equation results in separate estimates of the regression coefficients for each of the four levels of the factor *G*.

A second analysis was similar to the first except that first NDVI was regressed on stream order (SO), catchment size (CSA) and elevation (ELEV) using the model:

$$\mathrm{GLM(NDVI{\sim}SO + CSA + ELEV)}$$

In this case, the residual NDVI values were regressed on gabion treatment and precipitation with the model:

$$\mathrm{GLM}\left(\mathrm{RESID}{\sim}\frac{G}{1+\mathrm{precip}}-1\right).$$

This approach also produces separate regression equations for the effect of precipitation on NDVI for each of the four gabion treatments but, in this case, already having accounted for the potentially confounding effects of SO, CSA, and elevation.

2.4.3. Repeat vegetation survey analysis

Vegetation surveys and repeat photography were used to examine potential changes in plant species composition and cover associated with restoration activities. We compared vegetation observations immediately after cattle grazing ended on Cienega San Bernardino in 2000 to vegetation in approximately the same locations, 10 (or more) years later. Repeat surveys of the vegetation surveys done in 2000 were not possible because flooding and construction activity associated with restoration had removed the original survey markers.

3. Results

In the San Bernardino Valley, the average NDVI at control (random) sites declined in greenness over time ($y = -0.001x + 0.208$ [$R^2 = 0.093$]) in contrast to the treated areas that showed slight increases in greenness ($y = 0.0003x + 0.285$ [$R^2 = 0.008$]) over the same period (Fig. 6). Control sites started out as a lower NDVI value than treated sites (0.18 and 0.25, respectively), but dropped over time in contrast to a rise among treated sites (0.15 and 0.27, respectively). If this trend in difference continued at the same rate for 20 years from now – values would reach 0.3 vs. 0.14, making treated sites twice as green as the controls. Even more noticeable is the direct correlation in precipitation trends related to the control site greenness vs. the independence of the treated sites in relationship to drought (Fig. 6).

When these results are mapped out to spatially represent the change in NDVI over time, it is apparent that the majority of gabion sites are increasing and some very dramatically, where control sites are losing greenness naturally (Fig. 7).

Based on our statistical models, NDVI increased with precipitation for all treatment groups but the response varied among treatments (Fig. 8). For model 1, we regressed NVDI on precipitation and calculated separate regression coefficients for the four levels of the factor G, representing sites with and without gabions and before and after gabion construction. NDVI was higher on sites with gabions than on random sites. On sites with gabions, the slope of the regression equation of NDVI on precipitation was higher after construction than before construction (Student's $t = 2.11$, d.f. = 13,

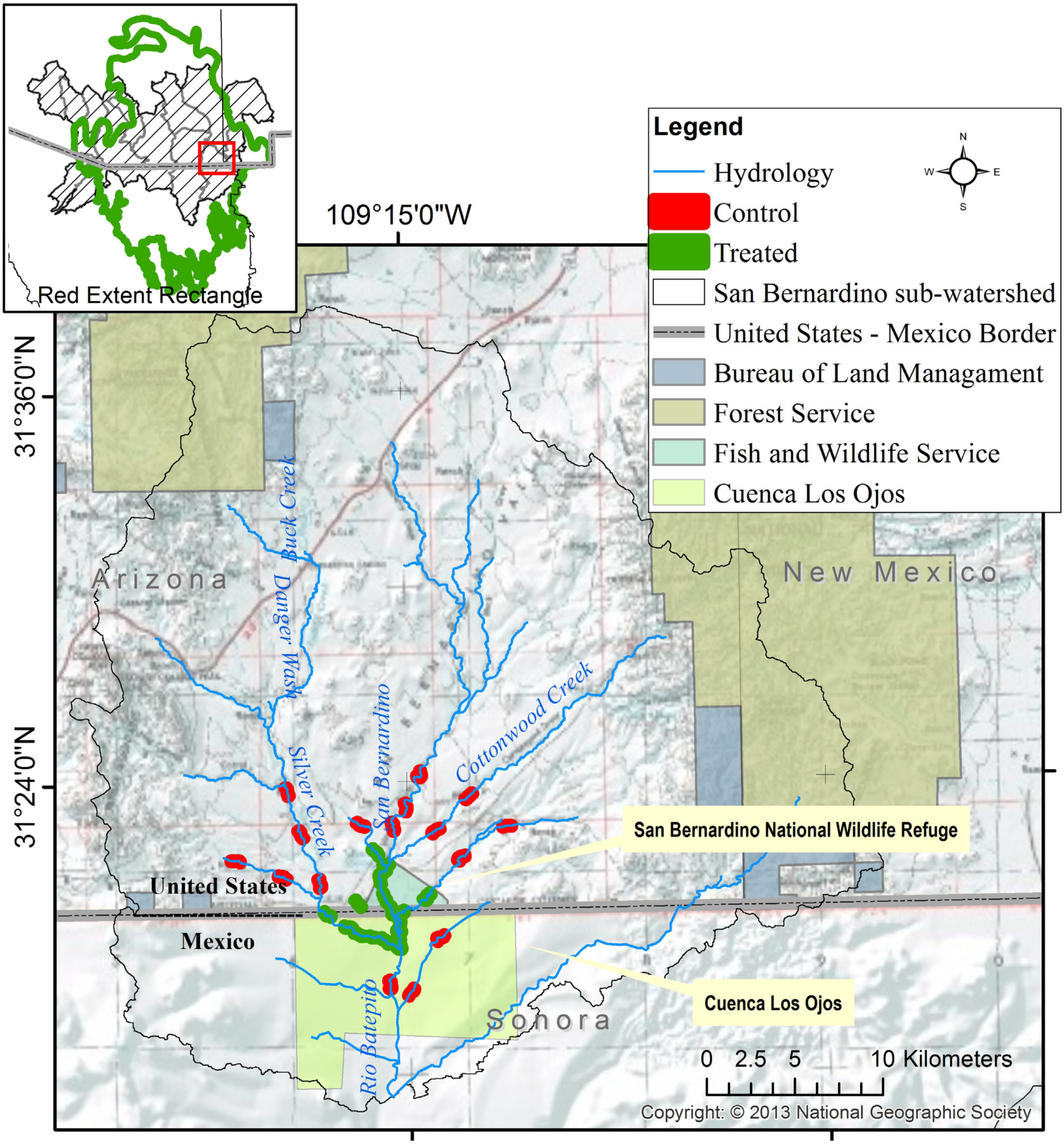


Fig. 4. Locations of treated and control sites within buffers at San Bernardino, Arizona, United States and Sonora, Mexico.

$p < 0.05$). However, NDVI was higher on sites with gabions than on random sites both before and after the construction of the first gabions, suggesting that the effect of gabion construction might be confounded by non-treatment differences between gabion and random sites.

NDVI increased with precipitation and was higher on sites with gabions. Separate regression lines for four treatments were estimated: (1) gabion sites before construction; (2) gabion sites after construction; (3) random sites before construction and (4) random sites after. In Model 1, raw NVDI values were regressed on precipitation and for Model 2 NVDI residuals after the effects of stream order, basin size and elevation were accounted for were regressed on precipitation (Fig. 8). Null deviance for Model 1 was 63.29 on 928 degrees of freedom, residual deviance was 8.18 on 920 degrees of freedom, and AIC is −1739.5. For Model 2, residual deviance was 6.033 on 920 degrees of freedom, and AIC was −2021.6.

Much of the difference between gabion and random sites is due to watershed characteristics of stream order, basin area, and elevation. When the effects of these confounding factors are removed, the effect of precipitation and gabion treatment are more clearly revealed. Random sites without gabions and gabion sites before treatment all respond similarly to precipitation, with higher NDVI in years with more rainfall. Gabion sites are distinguished by being more responsive to rainfall. In years of low rainfall, sites with

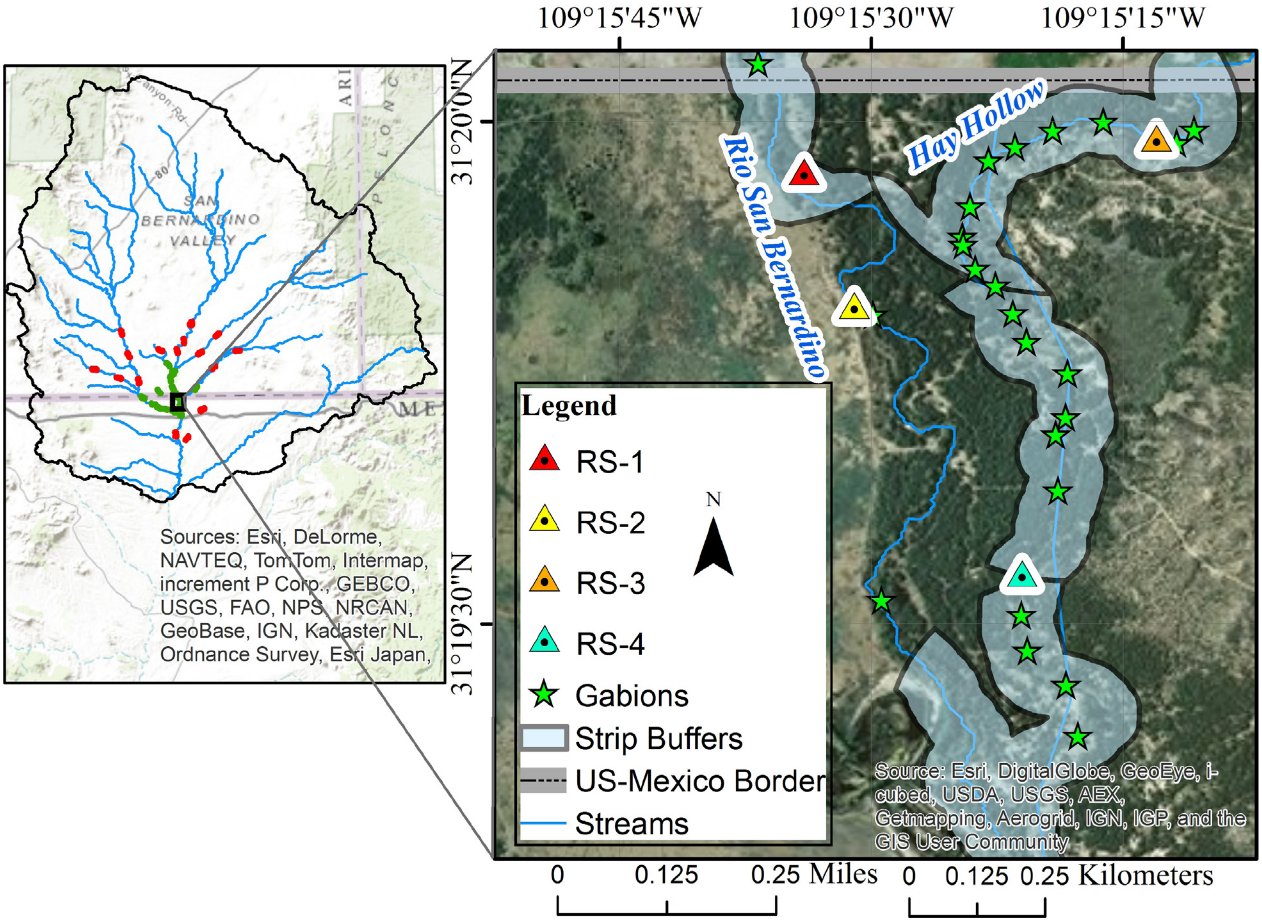


Fig. 5. Map displaying the four vegetation field sites on CLO on two different drainages, Rio San Bernardino (RSB) and Hay Hollow (HH), and relationship to gabions and buffers strips.

gabions have similar NDVI to the same sites before gabions were built and to sites where gabions were never built. However, NDVI on sites with gabions increases much more rapidly with increasing precipitation than on sites without gabions.

Where vegetation surveys were taken in 2000, more perennial plant species were found at sites along the Rio San Bernardino (RSB) due largely to the obligate aquatic species (*Juncus* spp., *Eleocharis parshii*) that occurred where there was permanent surface water

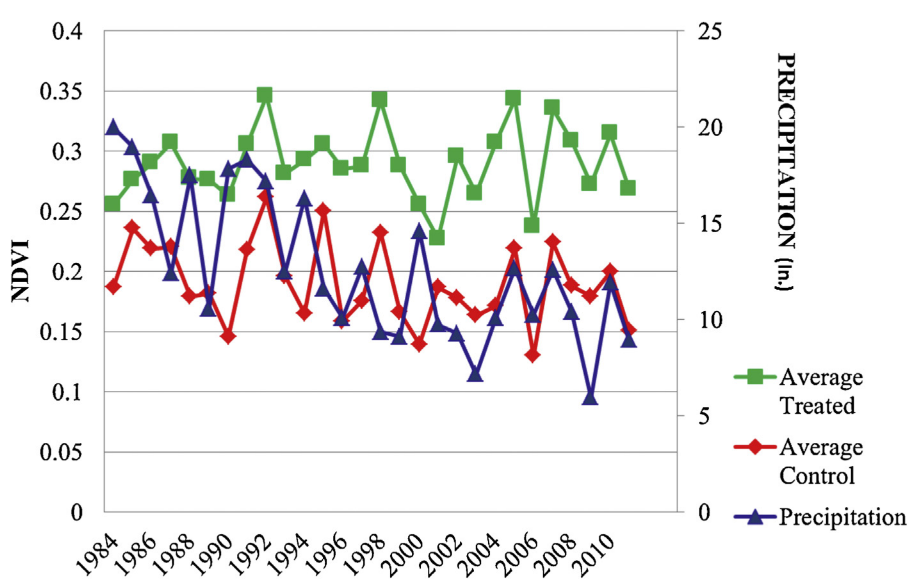


Fig. 6. Average NDVI plotted over time in San Bernardino at treated and control sites, in relationship to annual precipitation.

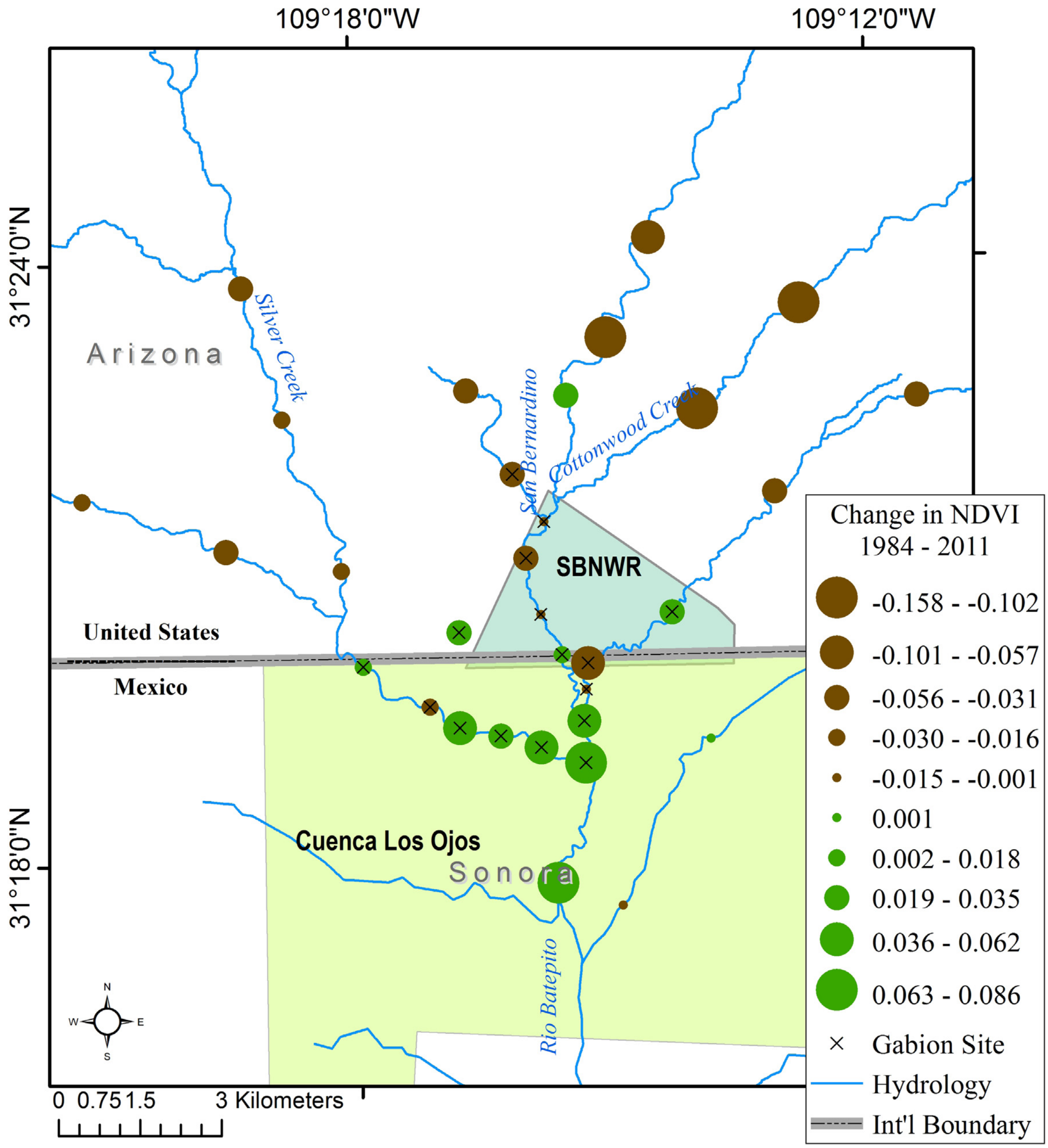


Fig. 7. Map of the results and spatial relationships of differencing the average NDVI values between 2011 and 1984, in the San Bernardino watershed, where green circles represent increasing greenness by size and brown circles portray decreasing greenness by size; gabion sites have "X" marked on them and controls are empty. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(Table 1). The same two exotic species (*Sorgum halpense*, *Cynodon dactylon*) occurred at all four sites. An average of 29% of the transects were not covered by vegetation (range 21–41%). Of the area covered by vegetation, exotic species were abundant and widespread on each transect, representing 37% of the total coverage (range 22–56%).

The lack of plant coverage indicated in the vegetation transects is consistent with the photograph taken in 1987 (Fig. 9A). The conspicuous tree species is *Salix gooddingii* and the shrub is *Baccharis salicicola*. Not evident, but likely covering much of the channel floor is the exotic, *Cynodon dactylon*. Where the water is visible in 1987, emergent aquatic species is either not present or has been cropped at the water surface by cattle. The photograph taken in 2009 (Fig. 9B) shows the addition of species and more plant biomass at this location. A young *Salix gooddingii* is present in the middle of the photograph and the river channel is largely obscured by *Typha domingensis* and *Juncus* spp. Sacaton grass (*Sporobolus wrightii*) is abundant in 2009 and not visible in 1987. This site is 20 m downstream of a gabion established in 1987 on the SBNWR.

Gabions accumulated substantial amounts of sediment and often did so rapidly (Fig. 10a–c). Fig. 10a, taken just as the gabion was completed, shows there is more than 2 m from the spillway to the streambed. In 2004, the bottom layer of the gabion and above is covered with stream deposited sediment. Plants emerging over the top of the spillway indicate that the upstream side has filled with sediment nearly completely. In Fig. 10c, taken in 2012, little of the gabion remains exposed on the downstream side, and the channel width is much reduced relative to that seen in the 2004

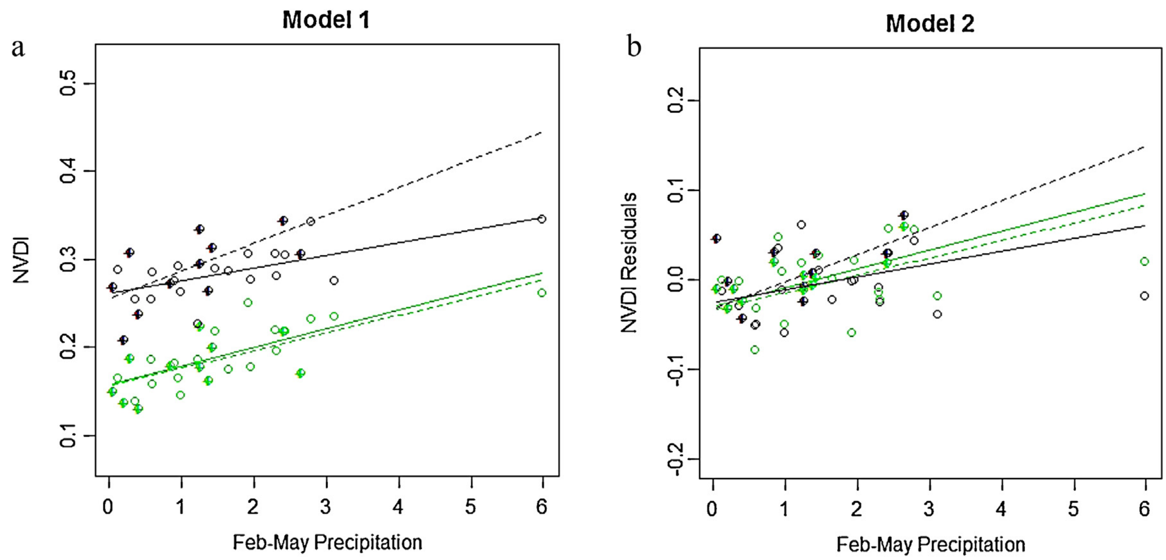


Fig. 8. Graphs displaying separate regression lines for each of the four treatments developed: (1) gabion sites before construction (black open circles and black solid line); (2) gabion sites after construction (black circles with pluses and dotted black line); (3) random sites before construction (green open circles and green solid line) and (4) random sites after construction (green circles with pluses and green dotted line). (a) depicts Model 1 and (b) depicts Model 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

photograph. The native grass, *Sacaton wrightii*, has established in front of the dam and much of the ground cover in the channel is bermudagrass (*C. dactylon*).

The large gabion visible furthest downstream in Fig. 11a is the same gabion seen in Fig. 10. This view from upstream shows that the channel width above this large gabion decreased considerably between 2002 and 2012 and a large stand of sorghum has become established on deeper sediments.

Fig. 12 is two pictures taken on the Rio San Bernardino where it is cross by Mexico Federal Highway 2 and 1 km downstream of the closest gabion. Although gabions may contribute to changes at this location, a large side tributary above this location floods regularly, making it likely that many of the changes observed here are due to removal of cattle. Fig. 12a is taken during the growing season of 2000, yet clearly shows the impact of grazing. Fig. 12b was taken 11 years later and despite the winter season, the establishment and growth of shrubs (*Baccharis sarothroides* and *Typha domingensis*) and trees (*Populus fremontii)* is notable.

4. Discussion

Our study suggests that gabion construction in Cienega San Bernardino has increased water availability to nearby vegetation above that observed for vegetation where gabions have not been installed. Functional cienegas are invariably associated with near-surface water (Minckley et al., 2013). Despite a general trend toward annual precipitation below the long-term average since gabion construction began in Mexico, NDVI indicates green up of vegetation around gabions slightly increased over a 10-year period in contrast to a slight decrease in the green up of vegetation away from gabions (Fig. 7). Furthermore, the response to between-year variation in February to May rainfall differed among sites with gabions and sites without gabions. If we controlled for catchment area and elevation (Model 2) or not (Model 1), sites with gabions had similar or higher NDVI values than sites where gabions were not present. The greatest difference in the response of vegetation around gabions and of vegetation at sites where gabions were not installed was in years of highest precipitation (Fig. 6). Overall, these changes are consistent with greater availability of subsurface water to vegetation in close proximity to gabions.

Data from vegetation surveys coupled with repeat photography before and after gabion construction on CLO suggest that plant biomass and species composition have changed. After gabions were constructed, abundance of the deep-rooted native grass (*Sacaton wrightii*) increased in the streambed (Fig. 9), and stands of the exotic grasses Sorghum, or Johnson's Grass (*Sorgum*

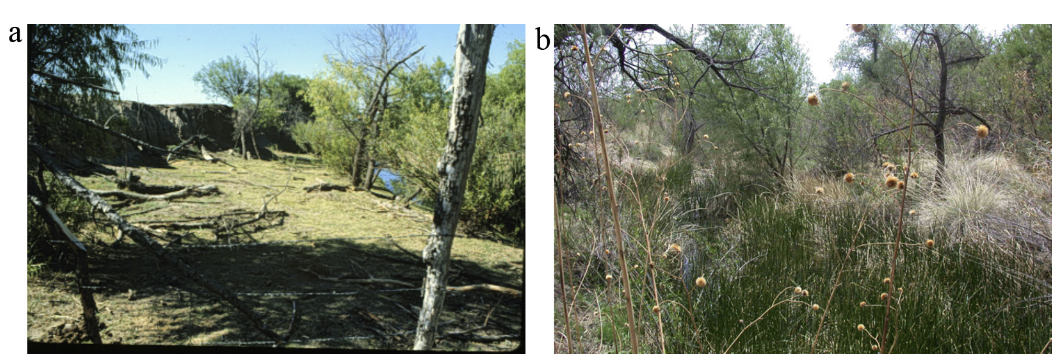


Fig. 9. Pictures taken at RS-1, looking downstream along the RSB from the US-Mexico border. (a) Photo taken in June 1987 suggests intense grazing (by D. Galat). Note the barb-wired fence demarcating the international border in the foreground and the river is just visible to the right. (b) Photo taken 29 April 2009, approximately 2–3 m to the west of (a) and 1 m south of the US-Mexico border, where the river is in the center but obscured by the growth of sedges (by RL Minckley).

Fig. 10. Pictures taken at RS-3, along Hay Hollow. (a) Photo taken on 27 October 2001, immediately following gabion construction – the spillway, in the center, is 2 m above the streambed (by Josiah Austin). (b) Photo demonstrates considerable sediment deposition below the gabion and grasses (*Sorgum halepense*) protruding behind the gabion indicate the upper side has large filled with sediment on 1 September 2004 (by Mark Austin). Note that the cottonwood tree on the left of the photograph (a) had died and fell before this was taken. (c) Photo taken on 12 June 2011 shows sedimentation and associated changes in the vegetation has continued (by RL Minckley).

halepense) and Bermudagrass (*Cynodon dactylon*) greatly expanded (Figs. 10 and 11). Young age classes of tree species, not present before gabions were constructed, are now common. Furthermore, aquatic plant species are present throughout the river. Many of these changes are due to decreased erosive effects of floods, one consequence of greater vegetation in the water channel. The exact contribution of gabions to vegetation changes is complicated because cattle were also removed within 5 years before gabion construction began on both SBNWR and CLO (Minckley, 2013). Cattle removal is a passive form of restoration that nevertheless has substantial effects on ecosystems; Hadley (1977) estimated that cattle removal in southwestern Colorado reduced sediment deposition and water runoff by more than 30%. Partitioning how much of the changes in vegetation reported here are associated with cattle removal and how much is due to gabion construction is not possible without more controlled comparisons. Nevertheless, vegetation observations from surveys and photographs in combination with remote imagery analysis strongly suggest gabions have increased the rate of vegetation changes above what would have occurred if these structures had not been installed.

The response of vegetation to gabions demonstrated here over a 10-year period suggests that long-term restoration of a mature

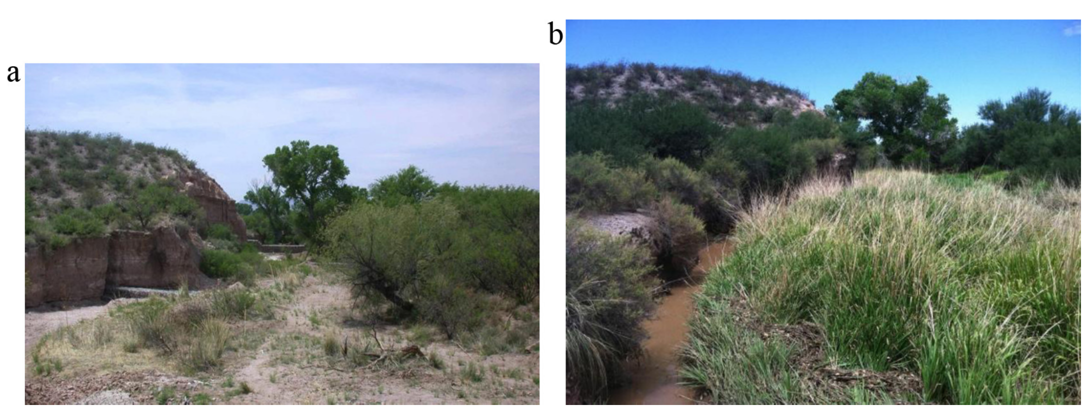


Fig. 11. Pictures taken at RS-3, Hay Hollow. (a) Photo taken 4 months after the two visible gabions were constructed, 29 April 2002 (by RL Minckley). (b) Photo taken 18 July 2012 shows the channel has narrowed considerably and a dense stand of Sorghum (*S. halepense*) has become established (by RL Minckley).

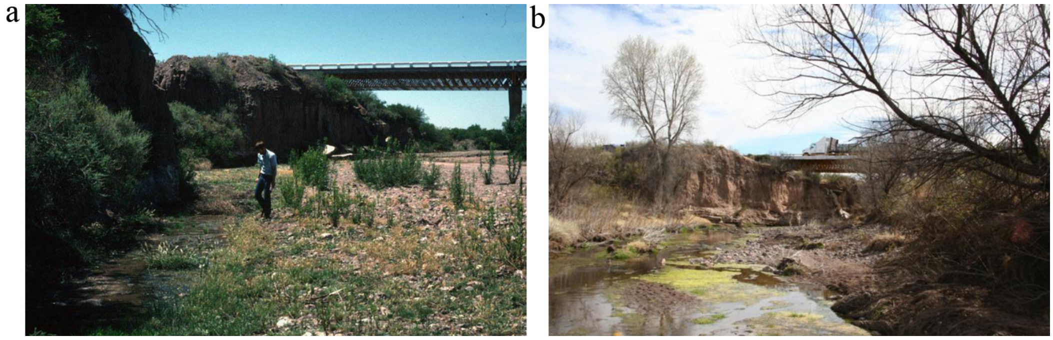


Fig. 12. Pictures taken upstream of the crossing with Mexico Federal Highway 2 and RSB. (a) Photo taken in the spring/summer of 2000, shortly after cattle were removed from the ranch. (b) Photo taken 11 February 2011 (photos by Josiah Austin).

cienega is possible. The RSB on CLO flowed through a deeply incised channel, 4–6 m below the cienega surface (Minckley and Brunelle, 2007), and photographs of the SBNWR taken in 1979 before grazing ended indicate the same conditions occurred there (Fig. 5 in Minckley, 2013). Gabion construction has resulted in rapid sediment accumulation (Fig. 10). This was seen as a negative in earlier studies of channel check dams as they would then breach the systems, but we note that if they fill up and the sediment supports an expanded riparian community, this is a positive result for cienega restoration, expanding the habitat value of the stream. However, water levels are increasing much slower based on observations of the extent of the remnant (= wetted) cienega and distribution of mesquite (*Prosopis juliflora*), a deep-rooted xeric adapted species sensitive to high water levels. Studies of paleovegetation and sedimentology indicate that cienega conditions fluctuate broadly depending on fluvial conditions (Heffernan, 2008; Minckley et al., 2013), and conditions on the cienega surface. Channelization of cienegas due to erosive water flows lowers the water table beyond the root zone of many plant species and reduces plant species richness and cover on the cienega surface. Both increased precipitation and anthropogenic manipulations such as canals, roads and other structures may produce nick points that initiate such channels from arroyo-cutting. Mature cienegas lack channels and may be highly resistant to channel formation despite large changes in fluvial conditions. For example, Cienega San Bernardino was dominated by deep-rooted trees and grasses under historic dry periods and lacked trees but had forbs and grasses when conditions of greater moisture prevailed (Minckley and Brunelle, 2007). Thus, the Cienega San Bernardino has repeatedly experienced and recovered from conditions similar to those observed there today. How quickly a mature cienega is restored will depend on hydrological conditions in the watershed that are little understood.

While stream flow is generated mostly in the higher elevations, the majority of sediment originates in ecosystems at lower elevations, like in the floodplains (Branson et al., 1981). Restoration efforts in side channels have likely reduced peak flows and stopped further headcutting, not demonstrated herein. Similarly, gabions installed in the upstream tributaries are likely impacting areas further downstream by raising the water table. Fig. 7 portrays an example of a control buffer strip located furthest south, demonstrating increased vegetation greenness. In a future analysis, we consider using areas downstream of infrastructure, where more effects of gabions might be further identified. This builds on Hendrickson and Minckley (1985) noting that cienegas are groundwater-storage reservoirs that dictate downstream hydrographs. Other ideas to build on this include capturing real-time measures of flow, and measuring infiltration rates downstream and in the focal streams. We also consider monitoring wells below the gabions to document recharge and storage capacities as well as impacts on base flow.

Check dams and gabions can protect arid landscapes from accelerated erosion due to episodes of high precipitation, common for monsoons in summer months, and also help to capture and store precious water supplies in predicted drier winter months. We conclude that when there is rain, the gabions are able to capture enough water to maintain and enhance vegetation. Quantifying the effect of check-dams on vegetation should further this discussion of biogeomorphology locally and prove useful in guiding public and private land managers to consider similar large-scale ecological restoration efforts on degraded riparian landscapes. We find that the installation of rock gabions is an important conservation and adaptation strategy that can reduce potential future impacts of climate change.

Acknowledgments

This research was conducted with support from the Land Change Science (LCS) Program of the USGS. Michelle Coe was supported by a University of Arizona/NASA Space Grant Undergraduate Research Internship. Partners contributing to this research should also be acknowledged for their great contributions, including Josiah and Valer Austin (Cuenca Los Ojos Foundation), Stephen DeLong (USGS), Richard Pritzlaff (Biophilia Foundation), and Pankaj Jamwal (Univ. of Arizona). We sincerely appreciate the careful peer reviews of this manuscript provided by Edward P. Glenn (University of Arizona) and William Radke (San Bernardino National Wildlife Refuge, U.S. Fish and Wildlife Service).

References

Antevs, E., 1952. Arroyo cutting and filling. J. Geol. 60, 375–385.

Anyon, R., Leblanc, S.A., 1985. The Galaz Ruin: A Prehistoric Mimbres Village in Southwestern New Mexico, 1st ed. University of New Mexico Press, Albuquerque.

Bahre, C.J., 1991. A Legacy of Change: Historic Impact on Vegetation in the Arizona Border lands. University of Arizona Press, Tucson.

Baker Jr., M.B., DeBano, L.F., Ffolliott, P.F., 1999. Hydrology and watershed management in the Madrean Archipelago. In: DeBano, L.H., Ffolliott, P.H., Ortega-Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B., tech. coords (Eds.), Biodiversity and management of the madrean archipelago: the sky islands of southwestern United States and northwestern Mexico. 1994. Sept. 19-23; Tucson, AZ. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 329–337.

Betancourt, J.L., Turner, R., (Ph.D.) 1993. Tucson's Santa Cruz River and the Arroyo Legacy. University of Arizona, Tucson, Arizona.

Branson, F.A., Gifford, G.F., Renard, K.G., Hadley, R.F., 1981. Rangeland Hydrology. Range Sciences Series 1, 2nd ed. Society of Range Management, Kendall Hunt Publishing Co., Dubuque, Iowa.

Brown, D.E., 1994. Biotic Communities: Southwestern United States and Northwestern Mexico. University of Utah Press, Salt Lake City.

Bryan, K., 1925. Date of channel trenching (arroyo cutting) in the arid Southwest. Science 62, 338–344.

Cooke, R.U., Reeves, R.W., 1975. Arroyos and Environmental Change in the American Southwest. Oxford University Press, London.
Cooley, M.E., Aldridge, B.N., Euler, R.C., 1977. Effects of the Catastrophic Flood of December 1966, North Rim Area, Eastern Grand Canyon, Arizona. U.S. Geol. Surv. Prof. Pap. 980, Washington, DC, pp. 1–43.
Cuenca Los Ojos, 2014. Gabions & Trincheras. Welcome to the Cuenca Los Ojos Foundation, Retrieved from http://www.cuencalosojos.org/gabions-cuenca-los-ojos.php
Curtin, C.G., 2002. Integración de La Ciencia y La Conservación Basada En La Comunidad En Las Tierras de La Frontera Entre México y Estados Unidos. Conserv. Biol. 16 (4), 880–886, http://dx.doi.org/10.1046/j.1523-1739.2002.00165.x.
Davies, P.M., 2010. Climate change implications for river restoration in global biodiversity hotspots. Restor. Ecol. 18 (3), 261–268, http://dx.doi.org/10.1111/j.1526-100X.2009.00648.x.
Davis, O.K., Minckley, T., Moutoux, T., Jull, T., Kalin, R., 2001. The transformation of Sonoran Desert wetlands following the historic decrease of burning. J. Arid Land Environ. 50, 393–412.
DeLong, S., Henderson, W.M., 2012. Can Erosion Control Structures in Large Dryland Arroyo Channels Lead to Resilient Riparian and Cienega Restoration? Observations from LiDAR, Monitoring and Modeling at Rancho San Bernardino, Sonora, MX (#EP23C-0825). Presented at the American Geophysical Union (AGU), Fall meeting, San Francisco, CA, http://fallmeeting.agu.org/2012/eposters/eposter/ep23c-0825/
Dominguez, F., Cañon, J., Valdes, J., 2010. IPCC-AR4 climate simulations for the Southwestern US: the importance of future ENSO projections. Climatic Change 99 (3), 499–514.
Fish, S.K., Fish, P.R., Varineau, R., Villalpando, E., 2013. In flight: Adriel Heisey's images of Trincheras Archaeology. In: An Exhibition of Arizona State Museum and the Mexican National Institute of Anthropology and History, http://www.statemuseum.arizona.edu/exhibits/heisey/index.shtml
Gass, L., Norman, L.M., Villarreal, M.L., Tolle, C., Coe, M., Jamwal, P., 2013. A Test of Methods to Measure Vegetation Change Adjacent to Gabions in Sonora, Mexico Using Landsat Imagery. Presented at the Santa Cruz River Researcher's Day, Tucson, Arizona, http://www.sonoraninstitute.org/images/stories/pdfs/Presentations/SCRResearchDays/2013/scrrd2013_gass_poster.pdf
Gibbs, J.P., 2000. Wetland Loss and Biodiversity Conservation. Conserv. Biol. 14 (1), 314–317, http://dx.doi.org/10.1046/j.1523-1739.2000.98608.x.
Hadley, R.F., McQueen, I.S., 1961. Hydrologic effects of water spreading in Box Creek basin, Wyoming (No. WSP - 1532-A). United States Geological Survey, Retrieved from http://pubs.er.usgs.gov/publication/wsp1532A
Haskett, B., 1935. Early history of the cattle industry in Arizona. Ariz. Hist. Rev. 6, 3–42.
Hastings, J.R., 1959. Vegetation change and arroyo cutting in southeastern Arizona. J. Ariz. Acad. Sci. 1, 60–67.
Heffernan, J.B., 2008. Wetlands as an Alternative Stable Sytaea in Desert Streams. Ecology 89 (5), 1261–1271, http://dx.doi.org/10.1890/07-0915.1.
Heller, N.E., Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol. Conserv. 142 (January (1)), 14–32, http://dx.doi.org/10.1016/j.biocon.2008.10.006.
Henderson, W.M., DeLong, S., http://fallmeeting.agu.org/2012/eposters/eposter/ep31c-0831/ 2012. Evaluating Dryland Ecological and River Restoration Using Repeat LiDAR and Hydrological Monitoring (#EP31C-0831). Presented at the American Geophysical Union (AGUS), Fall meeting, San Francisco, CA.
Hendrickson, D.A., Minckley, W.L., 1985. Cienegas: vanishing climax communities of the American South west. Desert Plants 6 (1984), 131–175.
Henshaw, A.J., Gurnell, A.M., Bertoldi, W., Drake, N.A., 2013. An assessment of the degree to which Landsat TM data can support the assessment of fluvial dynamics, as revealed by changes in vegetation extent and channel position, along a large river. Geomorphology, http://dx.doi.org/10.1016/j.geomorph.2013.01.011, http://www.sciencedirect.com/science/article/pii/S0169555X1300038X
Herold, L.C., 1965. Trincheras and Physical Environment Along the Rio Gavilan, Chihuahua, Mexico. Department of Geography, University of Denver, Denver.
Humphrey, R.R., 1987. 90 years and 535 Miles: Vegetation Changes Along the Mexican Border. University of New Mexico Press, Albuquerque.
Jemison, N.E., DeLong, S., Henderson, W.M., Adams, J., 2012. Evaluation of Arroyo Channel Restoration Efforts Using Hydrological Modeling: Rancho San Bernardino, Sonora, MX (#EP31A-0790). Presented at the American Geophysical Union (AGU) Fall Meeting, San Francisco, CA, http://fallmeeting.agu.org/2012/eposters/eposter/ep31a-0790/
Johansen, K., Phinn, S., 2006. Mapping structural parameters and species composition of riparian vegetation using IKONOS and Landsat ETM + Data in Australian tropical savannahs. Photogramm. Eng. Rem. Sens. 72 (1), 71.
Jones, K.B., Edmonds, C.E., Terrance Slonecker, E., Wickham, J.D., Neale, A.C., Wade, T.G., Riitters, K.H., Kepner, W.G., 2008. Detecting changes in riparian habitat conditions based on patterns of greenness change: a case study from the Upper San Pedro River Basin USA. Ecol. Indic. 8 (January (1)), 89–99, http://dx.doi.org/10.1016/j.ecolind.2007.01.001.
Kamber Engineering, 1990. "Chapter 3: Sediment and erosion control." An Inventory of Current Practices. 20460: U.S. Environmental Protection Agency, Office of Water Enforcement and Permits, Washington, DC, http://www.epa.gov/region6/6en/w/sw/sediment.pdf
Loik, M.E., Breshears, D.D., Lauenroth, W.K., Belnap, J., 2004. A multi-scale perspective of water pulses in dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 141 (October (2)), 269–281, http://dx.doi.org/10.1007/s00442-004-1570-y.
Lopes, V.L., Ffolliott, P.F., 1992. Hydrology and watershed management of oak woodlands in Southwestern Arizona. In: Ecology and Management of Oak and Associated Woodlands: Perspectives in the Southwestern United States and Northern Mexico, 224. USDA Forest Service General Technical Report RM-218. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 1877526, http://www.alibris.com/Ecology-and-management-of-oak-and-associated-woodlands-perspectives-in-the-southwestern-United-States-and-northern-Mexico-April-27-30-1992-Sierra-Vista-Arizona-Peter-F-Ffolliott/book/
Malcolm, J.W., Radke, W.R., 2008. Effects of riparian and wetland restoration on an avian community in Southeast Arizona USA. Open Conserv. Biol. J. 2, 30–36.
Malcolm, J.W., Radke, W.R., Lang, B.K., 2005. Habitat associations of the San Bernardino Springsnail, *Pyrgulopsis bernardina* (Hydrobiidae). J. Freshw. Ecol. 20, 71–77.
Marsh, J.A., (Master's thesis) 1968. The Effect of Suspended Sediment and Discharge on natural Infiltration of Ephemeral Streams. University of Arizona, Tucson, AZ, http://arizona.openrepository.com/arizona/bitstream/10150/191501/1/azu_td_hy_e9791_1968_245_sip1_w.pdf
Martin, P.S., 1963. The Last 10,000 Years. University of Arizona Press, Tucson.
Martin, P.S., Schoenwetter, J., Arms, B.C., 1961. Southwestern Palynology and Prehistory: The Last 10,000 Years. Geochronology Laboratories, University of Arizona, Tucson, AZ.
Mas, J.-F., 1999. Monitoring land-cover changes: a comparison of change detection techniques. Int. J. Rem. Sens. 20 (January (1)), 139–152, http://dx.doi.org/10.1080/014311699213659.
McDonald, B., 1995. The Formation and History of the Malpai Borderlands Group. In: DeBano, L.H., Ffolliott, P.H., Ortega-Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B., tech. coords (Eds.), Biodiversity and management of the madrean archipelago: the sky islands of southwestern United States and northwestern Mexico. 1994. Sept. 19-23; Tucson, AZ. Fort Collins, CO, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, pp. 483–486.
Miller, R., McQueen, I.S., Branson, F.A., Shown, L., Buller, W., 1969. An Evaluation of Range Floodwater Spreaders. Journal of Range Management 22, 246–247.
Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management? Earth 4, 20.
Minckley, R.L., 2013. Trajectory and rate of desert vegetation response following cattle removal. In: Gottfried, G.J., Ffolliott, P.F., Gebow, B.S., Eskew, L.G., Collins, L.C. (Eds.), Merging Science and Management in a Rapidly Changing World: Biodiversity and Management of the Madrean Archipelago III and 7th Conference on Research and Resource Management in the Southwestern Deserts. USDA Forest Service Proceedings RMRS-P-67. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Tucson, AZ.
Minckley, T.A., Brunelle, A., 2007. Paleohydrology and growth of a desert ciénega. Journal of Arid Environments 69 (3), 420–431, http://dx.doi.org/10.1016/j.jaridenv.2006.10.014.
Minckley, T.A., Turner, D.S., Weinstein, S.R., 2013. The relevance of wetland conservation in arid regions: a re-examination of vanishing communities in the American Southwest. J. Arid Environ. 88 (January), 213–221, http://dx.doi.org/10.1016/j.jaridenv.2012.09.001.
Nagler, P.L., Glenn, E.P., Huete, A.R., 2001. Assessment of spectral vegetation indices for riparian vegetation in the Colorado River delta, Mexico. Journal of Arid Environments 49 (1), 91–110, http://dx.doi.org/10.1006/jare.2001.0844.
Norman, L.M., Hirsch, D.D., Wesley Ward, A., 2008. Proceedings of a USGS Workshop on Facing Tomorrow's Challenges Along the U.S.-Mexico Border – Monitoring, Modeling, and Forecasting Change Within the Arizona-Sonora Transboundary Watersheds. U.S. Geological Survey Circular 1322, Tucson, AZ, http://pubs.usgs.gov/circ/1322/
Norman, L.M., Huth, H., Levick, L., Shea Burns, I., Phillip Guertin, D., Lara-Valencia, F., Semmens, D., 2010. Flood hazard awareness and hydrologic modelling at Ambos Nogales United States–Mexico Border. J. Flood Risk Manage. 3 (June (2)), 151–165, http://dx.doi.org/10.1111/j.1753-318X.2010.01066.x.
Omernik, J.M., 1987. Ecoregions of the conterminous United States. Ann. Assoc. Am. Geogr. 77 (March (1)), 118–125, http://dx.doi.org/10.1111/j.1467-8306.1987.tb00149.x.
Papoulias, D., 1997. Water Resources Issues in the Mexican Highlands Subarea. United States Department of the Interior U.S. – Mexico Border Field Coordinating Committee, www.cerc.usgs.gov/pubs/center/pdfDocs/90944c.pdf
Peterson, H.V., Branson, F.A., 1962. Effects of land treatments on erosion and vegetation on range lands in parts of Arizona and New Mexico. J. Range Manage. 15 (July (4)), 220, http://dx.doi.org/10.2307/3895254.
Peterson, H.V., Hadley, R.F., 1960. Effectiveness of erosion abatement practices on semiarid rangelands in Western United States. Int. Assoc. Sci. Hydrol. 53, 182–191.
Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20 (September (9)), 503–510, http://dx.doi.org/10.1016/j.tree.2005.05.011.
Pulliam, H.R., 2012. Borderlands Habitat Restoration Initiative. Presented at the Santa Cruz River Researcher's Day, Tucson, Arizona, http://www.sonoraninstitute.org/images/stories/pdfs/Presentations/SCRResearchDays/2012/pulliam_scrrd_2012.pdf
Quijada-Mascareñas, A., van Riper III, C., James, D.L., Lopez-Hoffman, L., Sharp, C., Gimblett, R., Scott, M.L., et al., 2012. Desarrollo de Un Programa de Monitoreo

a Nivel Ecosistema En El Muro Fronterizo México-Estados Unidos. In: En Cordova, A., de La Parra, C. (coordinadores), El Muro Fronterizo Entre México y Estados Unidos. Espacios Instrumentos y Actores Para Un Diálogo Constructivo. El Colegio de La Frontera Norte, Tijuana, México, pp. 165–185.

Sayre, N.F., 2005. Interacting effects of landownership land use, and endangered species on conservation of Southwestern US rangelands. Conserv. Biol. 19 (3), 783–792.

Schumm, S.A., Hadley, R.F., 1957. Arroyos and the semiarid cycle of erosion [Wyoming and New Mexico]. Am. J. Sci. 255 (March (3)), 161–174, http://dx.doi.org/10.2475/ajs.255.3.161.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.-P., et al., 2007. Model projections of an imminent transition to a more arid climate in Southwestern North America. Science 316 (May (5828)), 1181–1184, http://dx.doi.org/10.1126/science.1139601.

Skroch, M., 2008. Sky Islands of North America: a globally unique and threatened Inland Archipelago. Terrain.org. J. Built Nat. Environ. (Winter/Spring (21)), 147–152, Islands & Archipelagos.

Spector, S., 2002. Biogeographic crossroads as priority areas for biodiversity conservation. Conserv. Biol. 16, 1480–1487.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union 38 (6), 913–920.

Turner, R.M., Webb, R.H., Bowers, J.E., Hastings, J.R., 2003. The Changing Mile Revisited. University of Arizona Press, Tucson, pp. 334.

U.S. Environmental Protection Agency, 2010. Ecoregions of North America. U.S. EPA Office of Research & Development (ORD) – National Health and Environmental Effects Research Laboratory (NHEERL), http://www.epa.gov/wed/pages/ecoregions/na_eco.htm#Downloads

U.S. Fish and Wildlife Service, 1979. Proposed Land Acquisition, San Bernardino Ranch, Cochise County, Arizona: Environmental Assessment. USFWS, Albuquerque, NM.

Villarreal, M.L., Van Leeuwen, W.J.D., Romo-Leon, J.R., 2012. Mapping and monitoring riparian vegetation distribution structure and composition with regression tree models and post-classification change metrics. Int. J. Rem. Sens. 33 (July (13)), 4266–4290, http://dx.doi.org/10.1080/01431161.2011.644594.

Vogt, B.J., http://www.Geochange.Er.Usgs.Gov/sw/impacts/geology/arroyos/ (Updated December 1) 2003. The Arroyo Problem in the Southwestern United States. Produced for the USGS.

Wagoner, J.J., 1952. History of the Cattle Industry in Southern Arizona, 1540–1940. Univ. Ariz. Soc. Sci. Bull. 20, 1–132.

Wagoner, J.J., 1960. Overstocking ranges in southern Arizona during the 1870's and 1880's. Arizoniana 2, 23–27.

Warshall, P., 1995. The Madrean Sky Island Archipelago: A Planetary Overview. In: DeBano, L.H., Ffolliott, P.H., Ortega-Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B., Tech. Coords (Eds.), Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico. 1994 Sept. 19-23; Tucson, AZ, 6–18. Gen. Tech. Rep. RM-GTR-264. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Waterfall, P., 2004. Harvesting Rainwater for Landscape Use, http://arizona.openrepository.com/arizona/handle/10150/144824

Webb, R.H., Leake, S.A., 2006. Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the Southwestern United States. J. Hydrol. 320 (April (3–4)), 302–323, http://dx.doi.org/10.1016/j.jhydrol.2005.07.022.

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall- Erosion Losses. In: A Guide to Conservation Plannings (Agriculture Handbook No. No. 537), Washington: USDA, Retrieved from http://topsoil.nserl.purdue.edu/usle/AH_537.pdf

Woodard, D.G., Durall, R., 1996. United States-Mexico Border Area, as Delineated by a Shared-water Resources Perspective. Fact Sheet 1. U.S. Department of the Interior.