REVISED FINAL REPORT
Test of Riparian Recovery Following Reduced Groundwater Pumping, Lower San Pedro River

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I. INTRODUCTION

Background & Overview

Hundreds of millions of dollars have been spent on stream restoration in the Southwest since 1989 (Follstad Shah et al. 2007). Though restoration measures vary widely among projects, most include revegetation activities. Many follow a historically-used approach of planting desired species and/or removing undesired species. A novel restoration approach has been pioneered along the lower San Pedro River by the Nature Conservancy of Arizona (TNC) and other collaborating groups (Katz et al. 2009). TNC recently purchased two farms (H&E Land and Cattle property near Mammoth, and Three Links Farm near Cascabel) that formerly pumped large quantities of alluvial groundwater for crop irrigation, and reduced pumping rates to negligible levels. The management objective is to improve aquatic and riparian ecosystem conditions by restoring surface water and groundwater hydrology through cessation of groundwater pumping. As such, this approach focuses on restoring the physical processes that underpin ecosystem characteristics. The assumption is that the biotic components of the aquatic and riparian ecosystems will recover spontaneously following restoration of the hydrologic regime. This is an innovative approach to restoration that, if successful, could provide a model for work at other sites on the San Pedro River and in other river basins.

There is a significant need to document the results of this hydrologic restoration strategy to assess its effectiveness and applicability to other settings. While the number of river restoration projects in the US has increased exponentially since 1990 (NRRSS 2005), relatively little funding or research has been invested in monitoring and evaluation of restoration outcomes (Bernhardt et al. 2005). Monitoring rates in the Southwest are higher than the national average, with >25% of restoration projects include monitoring (Follstad Shah et al. 2007). However, more monitoring and evaluation is needed. The lack of information about the results of specific restoration techniques and projects constitutes a missed opportunity for scientific learning, and for advancement of the field of restoration practice. Restoration research (including data collection before, during, and after restoration) can potentially provide valuable information about basic ecosystem characteristics and functions, as well as about the efficiency and effectiveness of restoration strategies (Palmer et al. 2005).

This grant funded the first phase of a long-term research project aimed at monitoring and assessment of the hydrologic restoration experiment being conducted on the lower San Pedro River. This research constitutes an on-the-ground test of the hypothesis that riparian degradation can be reversed by a management strategy focused on restoration of groundwater levels and base flows. Specifically, we address the question of whether restoration of groundwater levels and base flows on an un-dammed semi-arid region river will result in recovery of the biotic riparian ecosystem components on formerly degraded reaches. There is a growing body of research examining vegetation-hydrology linkages in riparian ecosystems (e.g., Auble et al. 1994, Stromberg et al. 1996, Shafroth et al. 2000), and a number of conceptual and computer models suggest that riparian vegetation should recover spontaneously following hydrologic restoration (e.g., Poff et al. 1997, Mahoney and Rood 1998, Richter and Richter 2000, Lite and Stromberg 2005). However, recent published tests of this idea have focused on restoration of flood flows (Rood et al. 2005), or minimum instream surface flows (Poff et al. 1997, Hughes and Rood 2006). Despite the documented importance of base flows and groundwater to river and riparian ecosystems (Rood et al. 1995, Scott et al. 1999, Horton et al. 2001, Amlin and Rood 2003, Cooper et al. 2003, Eamus et al. 2006), few studies have assessed restoration of groundwater levels as a riparian restoration strategy in arid environments (except see Hou et. al 2006, Chen et. al 2008).

Our ability to assess restoration responses in this system relies upon a foundational body of research on the San Pedro River conducted over the past decade. This work has identified relationships between vegetation characteristics and site hydrology (e.g., Stromberg et al. 1996, Lite and Stromberg 2005, Stromberg et al. 2005, Bagstad et al. 2006, Lite et al. in review). For example, Lite and Stromberg (2005) examined cottonwood-willow versus tamarisk basal area, canopy cover, and importance value in relation to site hydrologic condition and found that cottonwood-willow tended to be dominant at sites with surface flow permanence >76%, groundwater depth <2.6m, and annual groundwater fluctuation <0.46m. At drier sites, tamarisk was dominant. They therefore argued that hydrologic thresholds for maintaining cottonwood-willow forests exist on this river, and that stream dewatering and groundwater decline can cause shifts to tamarisk dominance. Hydrologic thresholds for the maintenance of herbaceous vegetation types also exist on the San Pedro River, with riverine marshes limited to reaches with perennial flow (Stromberg et al. 2005).

The observation that San Pedro River riparian vegetation exhibits a threshold response to hydrologic condition suggests the potential for hydrologic restoration at de-watered sites to result in ecosystem recovery. However, such recovery has not been demonstrated, and the possible rates and pathways of ecosystem response are unknown. Certainly, one possible scenario is that the process of vegetation change following stream dewatering is reversible. In this case, which has been termed ‘successional’ recovery (Suding et. al 2004), hydrologic restoration will result in predictable vegetation response over short time scales. However, other scenarios are possible. For example, the degraded system may be resistant to change due to shifts in physical environmental conditions or biotic factors, and ecosystem response to restoration may be unpredictable (Suding et. al 2004). This may be especially true in semi-arid regions where vegetation and fluvial geomorphic change can be slow, and for relatively long-lived organisms such as trees which may exhibit a considerable lag time in their response to altered hydrology (Katz et. al 2005). Earlier work by Stromberg (1998) suggested that relative abundances of cottonwood-willow and tamarisk have changed through time along the lower San Pedro River. However, time-scales and rate of change, and the degree to which vegetation may exhibit a lag time in its response to hydrologic amelioration, are not known. Vegetation can exhibit 'inertia', with certain plant species continuing to remain dominant despite incremental changes in environmental factors such as groundwater level. Major environmental change, such as large flooding, may be required to bring about vegetation shifts and reverse historical vegetation changes.

In addition to expanding scientific understanding of hydrologic restoration, our research has produced practical information for managers and includes an outreach component. For many managers, a key aspect of ecosystem recovery in this system would be shifts from tamarisk shrublands to cottonwood-willow forests at restored sites. Indeed, tamarisk removal has been pursued at considerable effort and expense on many rivers in the Southwest (Shafroth et al. 2005). Another important management goal on the lower San Pedro River is maintenance of riparian vegetation patches suitable to support breeding populations of the endangered southwestern willow flycatcher (Munzer et al. 2004). By assessing vegetation conditions and changes on the lower San Pedro River, our research will inform management of this important conservation landscape.

Such efforts are best undertaken in collaboration with community partners. Therefore, as part of this research we have developed a working relationship with the Community Watershed Alliance of the Middle San Pedro Valley (CWA), a community group working in the Benson area sub-watershed of the San Pedro River (http://www.cwatershedalliance.com/). We have worked with CWA to establish three riparian monitoring sites, and have collaborated in data collection since 2007. All research described in this report was subcontracted by Coronado RC&D to Dr. Gabrielle Katz (Appalachian State University) and Dr. Juliet Stromberg (Arizona State University).

<u>Goals & Objectives</u>

The overall goal of this project was to test the effectiveness of a hydrologic-based approach to riparian ecosystem restoration on the lower San Pedro River. We tested the idea that streamside wetland communities (of comparable composition and diversity to reference conditions) would develop as stream flows once again became perennial, and that shifts from tamarisk to cottonwood-willow forests could be accomplished solely by modifying the hydrologic regime. More broadly, we tested the idea that riparian vegetation can re-establish at sites historically degraded by groundwater pumping and stream dewatering, following hydrologic improvement, without need for restoration plantings.

To this end, we collected baseline data at seven restoration research sites in 2002 and 2003, and collected data on a subset of vegetation metrics annually thereafter. We also studied five reference sites on the lower San Pedro River, and three additional reference sites were established (with CWA) as part of this project. At most sites hydrology was monitored monthly or quarterly by TNC. We initiated re-sampling of all field sites in 2007, funded by a grant from USGS. Funding from AWPF was used to finalize the re-sampling and complete the data analysis. This funding provided for one year of data collection (2008), and for data analysis and synthesis. This allowed us to assess the vegetation and geomorphic changes that have occurred since project initiation, and to interpret these results in the context of vegetation-hydrology relations on the San Pedro River (Stromberg et al. 1996, Lite and Stromberg 2005). Our research sheds light on the reversibility of riparian degradation, and on the lag-times, rates of change, and possible hydrologic thresholds of restoration in this setting.

Objectives:

1. Document trends in controlling variables
   We collected data on pre-monsoon summer dry season streamflow presence at all sites annually. We also examined surface flow records for the San Pedro River, and groundwater monitoring data for the study period.

2. Document short-term indicators of riparian ecosystem change
   Certain ecosystem characteristics tend to be especially responsive to hydrologic conditions; these short-term indicators should exhibit the earliest response to hydrologic improvement. The short-term hydrologic indicator targeted in this project

was streamside herbaceous vegetation. We assessed streamside herbaceous vegetation in terms of species composition, cover, and weighted Wetland Indicator Score (USDA-NRCS 2006), and examined changes over time.

3. Document long-term indicators of riparian ecosystem change
   Many important ecosystem characteristics are likely to change slowly in response to hydrologic improvement. Our study was designed to document patterns of change (e.g., whether there are lag times, threshold-type responses, or steady incremental adjustments) in these parameters. Long-term indicators targeted in this study were riparian vegetation patch types, floodplain woody vegetation structure, and channel and floodplain geomorphology.

4. Assess patterns of change and vegetation-hydrology relationships
   Once we collected data on short- and long-term indicators of change, we analyzed this information to (1) identify patterns of change at the restoration sites, and (2) compare these changes to those observed at the reference sites, and to those predicted by the results of other research.

II. METHODS

A. Study Area

Study River. This study was conducted on the San Pedro River, an un-dammed river that flows northward from its headwaters in Sonora, Mexico, to its confluence with the Gila River near Winkelman, Arizona (Figure 1). The San Pedro River is spatially intermittent; perennial-flow reaches with year-round surface flow are interspersed with non-perennial reaches characterized by channels that are dry for part of the year. The locations of perennial reaches are determined primarily by bedrock geology, as well as by permeability of the basin-fill deposits, and proximity to tributaries and areas of groundwater pumping (Katz et al. 2009).

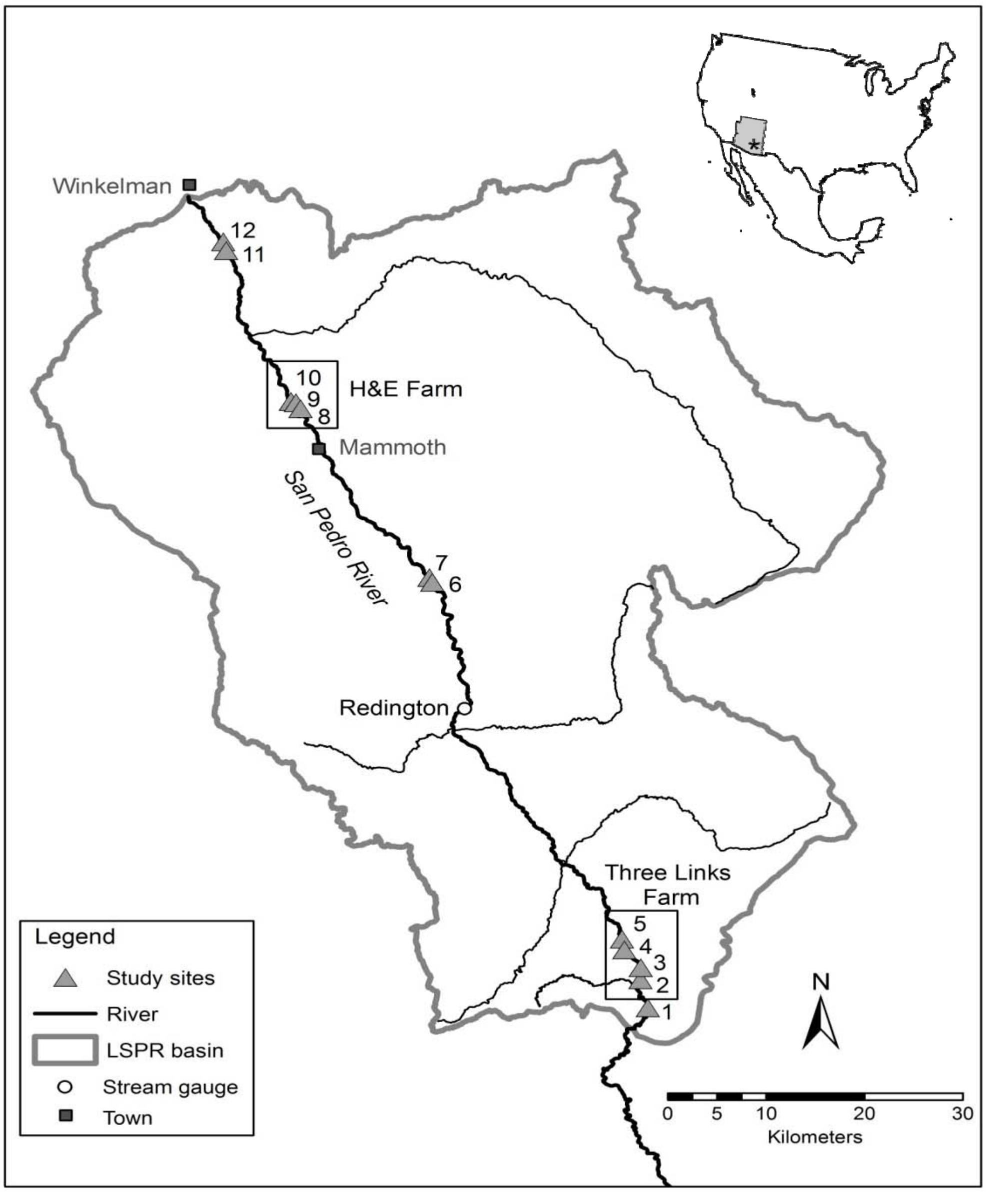

Figure 1. Map of the study area.

The San Pedro River experienced a regime shift within the past two centuries, creating the current configuration of the river system. Prior to the mid-19th century, the river meandered across its floodplain and supported fluvial wetlands, *Sporobolus wrightii* grasslands, scattered riparian forests, and beaver populations along much of its length (Webb & Leake 2006, Huckleberry et al. 2009). Beginning in the 1880s the river down-cut and then widened in a process of arroyo formation observed on many rivers in the Southwest (Hereford & Betancourt 2009). The new geometry stabilized in the 1940s to 1950s, with abundant riparian forest on the inset floodplain (Webb & Leake 2006). Today, the principal woody species on the active floodplain include *Populus fremontii* and *Salix gooddingii*, as well as the introduced Tamarix which dominates drier reaches (Lite and Stromberg 2005). *Prosopis velutina* is the primary tree on the river terraces. Agricultural activities along the river, including livestock grazing and irrigated crop production on river terraces, are probable contributors to the prevalence of many non-native species in the streamside herbaceous community, including *Rorippa nasturtium-aquaticum, Polypogon monspeliensis, Cynodon dactylon*, and *Melilotus* spp. Beaver, fluvial marshlands, and *Sporobolus* grasslands are uncommon in the new riparian system. In light of this history, the restoration target was not defined as a return to pre-entrenchment conditions, but as attainment of wetter conditions on the post-entrenchment river and floodplain.

Some reaches of the LSPR sustain perennial streamflow and shallow alluvial water tables, conditions necessary for the maintenance of ecologically important *Populus fremontii-Salix gooddingii* forests and riverine marshlands. However, many reaches of the LSPR have been degraded by groundwater pumping for agricultural irrigation and mining activities (Haney 2002, Haney 2005), and streamflow at Redington, AZ has declined by 70% since the mid-1940s (Thomas 2006). In some areas, groundwater and surface water levels in the riparian zone have declined below threshold levels needed to sustain *Populus-Salix* forests and emergent wetlands (Lite and Stromberg 2005, Stromberg et al. 2005). In such areas, *Tamarix* spp. (*chinensis, ramosissima*, or hybrids) and *Hymenoclea monogyra* shrublands dominate the floodplain, and the stream channels are wide and dry, supporting little herbaceous vegetation or aquatic life. While the riparian zone has been impacted by a variety of human activities (e.g., livestock grazing, ATV use), hydrologic alterations from groundwater pumping are thought to have had an over-riding influence on ecosystem characteristics.

<u>Study sites</u>. Our network of long-term riparian monitoring and research sites includes six restoration sites and six reference sites on the LSPR (Figure 1, Table 1). Restoration study sites were located at two farms purchased by The Nature Conservancy of Arizona (TNC), where historic alluvial groundwater pumping was curtailed to meet restoration objectives (Haney 2005; Katz et al. 2009). Three sites were located at the 870 hectare Three Links Farm which supported an upstream reach that maintained perennial flow even during historic pumping. Downstream of this reach the river was historically non-perennial due to pumping impacts. According to anecdotal evidence (including overflight observations, aerial photography, and on-the-ground observations), surface flow extent was substantially reduced on the farm during irrigation periods (TNC, unpublished data) suggesting that flow was perennial prior to agricultural pumping. The restoration study sites were located in irrigation-impacted reaches within 4 km of the upstream perennial flow reach. Three Links Farm formerly contained 425

hectares under irrigated agriculture, with groundwater pumping rates of ~3,947,165 cubic m per year. Irrigation pumping was terminated in August 2002 (prior to data collection).

Table 1. Study site information.

Site no.[1]	Name	Code	Type
1	Narrows	NRW	Non-perennial reference
2	Three Links P	3LP	Perennial Reference
3	Three Links 1	3L2	Restoration
4	Three Links 2	3L3	Restoration
5	Three Links 3	3L4	Restoration
6	Spirit Hollow I	SHI	Non-perennial Reference
7	Spirit Hollow P	SHP	Non-perennial Reference[2]
8	H&E 1	HE1	Restoration
9	H&E 2	HE2	Restoration
10	H&E 3	HE3	Restoration
11	TNC Preserve I	TNCI	Perennial Reference
12	TNC Preserve P	TNCP	Perennial Reference

[1]Site numbers corresponds to Figure 1. Note that three additional study sites were established near Benson in 2007, but are not shown on the map. [2]Perennial in 2003, non-perennial thereafter.

The three other restoration study sites were located at the 214 hectare H&E Farm (Figure 1), located 17 km downstream, and 6 km upstream, of the nearest perennial flow reaches. Groundwater pumping rates were ~2,713,676 cubic m per year at H&E Farm prior to irrigation cessation in 2001. Groundwater levels were ~2.5 m higher in monitoring wells immediately following irrigation retirement compared to 1998 readings (TNC, unpublished data). All restoration sites were non-perennial during historic farm operation. At both farms, floodplain terraces formerly supporting *Prosopis velutina* bosques had been cleared and used for crop agriculture. Direct impacts of agriculture did not occur on the active floodplain, where our research was conducted. During our study, livestock were excluded from the floodplain by fences at both farms, though occasional trespass cattle did access the floodplain in most years.

Reference sites were located upstream and downstream of the restoration sites, and included representative target conditions (sites with perennial flow) as well as those with non-perennial flow (Figure 1, Table 1). One reference site was located at Three Links Farm in the perennial upstream reach that had not been impacted by irrigation pumping. The remaining five reference sites were established for prior research (see Bagstad, et al. 2005, Lite et al. 2005), and were located in riparian preserves (e.g., Salt River Project's Spirit Hollow Preserve, TNC's San Pedro River Preserve) or on state land. Based on monthly monitoring, the degree of stream intermittency at the non-perennial sites (i.e., the percent of time surface flow was absent) ranged from 4 to 71% (see Bagstad, et al. 2005, Lite et al. 2005). During our study, the floodplains were fenced for cattle exclusion at all reference sites except for Narrows. However, occasional trespass cattle did access the floodplain.

In 2007 we established three additional reference sites in the Benson area, in collaboration with the Community Watershed Alliance of the Middle San Pedro Valley (CWA). These sites have been monitored annually for streamside herbaceous vegetation (2007-2009), and woody floodplain vegetation was described at these sites in 2008. These sites are located upstream of the Narrows, which is the geologic division between the upper and lower San Pedro River basins.

Weather and stream flow conditions. The climate in the study area is semi-arid. Annual precipitation tends to occur in two distinct seasons associated with monsoonal convective storms in summer and low-intensity frontal storms in winter. Mean annual precipitation at Cascabel, Arizona is 35 cm (for 1969-2007), with 13 cm occurring in winter/spring (December through May) and 22 cm occurring in summer/fall (June through November; Western Regional Climate Center 2008). During the restoration period, annual precipitation tended to be lower than average, especially in 2002 (20.9 cm) and 2003 (22.4 cm). The generally dry conditions were punctuated by occasional wet periods that produced high summer monsoon flows in 2005 and 2006 (Figure 2).

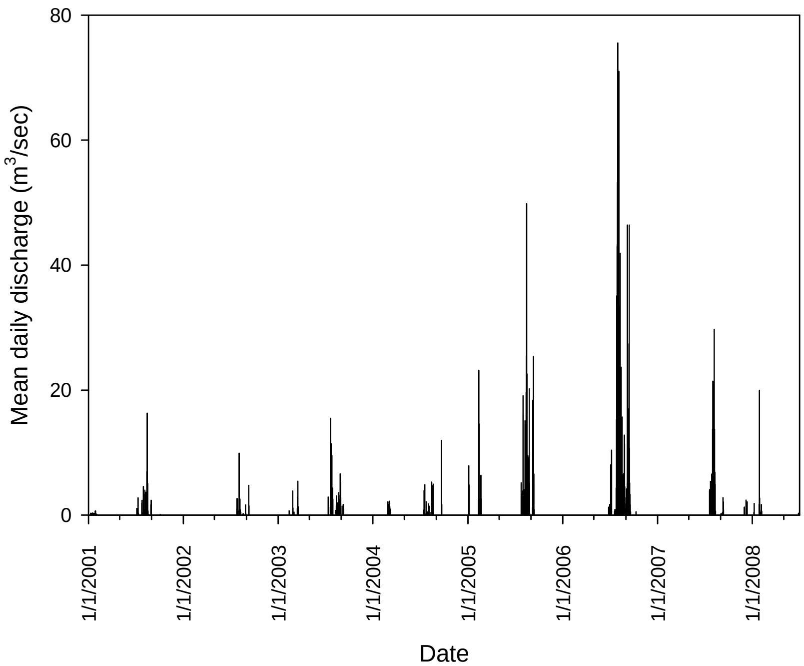

Figure 2. Mean daily discharge at Redington, Arizona. Period depicted: January 1, 2001 to July 1, 2008 (USGS gauge # 09472050).

B. Field Methods

Field sampling: Streamside herbaceous vegetation

Streamside herbaceous vegetation was sampled annually during the pre-monsoon summer dry-season (late May – early June) for six years (2003-2008). In the dry season, herbaceous riparian vegetation patterns most strongly reflect river and groundwater hydrology, as opposed to being influenced by precipitation or flood pulses (Lite et al. 2005). The streamside zone was defined as the zone of direct influence of the low-flow stream channel, including channel bars, benches and streambanks, and inclusive of areas with shallow water (up to 10cm) and emergent aquatic vegetation. At each site data were collected at three stream locations, separated by a stream distance of 100m. Percent cover of each herbaceous species was estimated within 1-m^2 plots (6 per stream location, 18 total per site) using modified Domin-Krajina cover classes (Müller-Dombois & Ellenberg 1974). In 2007 and 2008, percent cover of overhanging woody vegetation was also recorded in each plot. Presence or absence of May-June surface flow was noted for each field sampling date, and data were used to categorize sites as perennial (i.e., May-June flow present in all years) or non-perennial.

Figure 3. Streamside sampling field work. Use of 1-m2 plot frame to sample streamside herbaceous vegetation at restoration site HE1.

Field sampling: Woody floodplain vegetation

In 2002/2003 and 2007/2008 we documented woody vegetation on two floodplain transects at each site. Transects were 100m apart, were oriented perpendicular to the channel, and spanned the width of the floodplain at each site. We identified discrete floodplain patches along both transects based on observed vegetative and geomorphic discontinuities. Patches consisted of relatively homogeneous areas (in terms of floodplain surface type, and species composition, density, foliage volume, and age/size structure of woody populations). We recorded patch width and patch distance from the channel edge for each patch. Within each patch, we noted the dominant woody species composition, and measured the dbh of the two largest stems of the dominant species (occurring within in a 20 m belt centered on the transect line). Vegetation volume within each canopy height class (>5 m, 1-5m, <1 m above the ground surface) was estimated according to four categories (61-100%, 26-60%, 11-25%, 0-10% vegetation volume, inclusive of foliage and wood). The height and species of the tallest tree in each floodplain transect was also recorded.

On one transect at each site, detailed woody vegetation data was collected in plots within each patch. At least one woody data collection plot was located within each patch (as delineated above). For patches wider than 25m (patch width = distance along transect), additional plots were added. For example, for plots 25m – 50m wide, two plots were distributed equally along the transect line. For plots 50m – 75m wide, we sampled three plots, etc. Plots were randomly/regularly located within the patch, but were centered on the transect line and did not extend more than 10m to either side of the transect line. Plots were 100 m2 (generally 5m x 20m) centered on the transect line and extending 10m to each side of it. Within each plot, we recorded woody stem density/basal area, tree canopy volume, and canopy cover by species. For each tree or shrub species, we measured the basal diameter to the nearest 0.5 cm of each stem rooted within the plot. Vegetation volume was recorded at two measurement points per plot using a telescoping line intercept pole. Data were recorded as the foliage volume by species within 1m height increments (subdivided into "decimeters" for data collection).

Field sampling: Hydrology and geomorphology

The presence or absence of surface flow at each site was recorded annually at the pre-monsoon summer dry season sampling date for streamside herbaceous vegetation. Groundwater levels (m) were monitored quarterly at the restoration sites in floodplain piezometers (H&E Farm) or retired irrigation wells (Three Links Farm) by TNC. Well locations were surveyed using a Total Station to present well monitoring data as water depth below the thalweg at each site assuming a level horizontal water table. We surveyed floodplain cross sections with a Total Station at ten sites in 2008. The surveyed sites were: 3LP, 3L2, 3L3, 3L5, HE1, HE2, HE3, TNCP, TNCI, CWA2, and CWA3. Due to time constraints and problems with site access, sites 3L4, Narrows, CWA1, SHI and SHP were not surveyed.

Figure 4. Survey field work. Left panel: the Total Station surveying instrument, rented from Holman's in Tempe, Arizona. Right panel: the prism (sighting target for survey instrument). Photos: W. Gandy.

C. Data Analysis

Analysis: Streamside herbaceous data

Plant species were classified according to water availability needs using wetland indicator scores for the Southwest (Region 7; USDA-NRCS 2007). Wetland indicator scores signify the probability that a species will occur in a wetland environment. For our study, obligate and facultative wetland species were grouped as as hydric; facultative and facultative upland as mesic; and non-wetland as xeric. Plants also were categorized into six functional groups based on combinations of life history (annual or perennial) and water needs categories (Bagstad et al. 2005).

Several vegetation metrics (total herbaceous cover, species richness, weighted wetland indicator score, relative cover of non-native species, and relative cover of species within the six functional groups) were compared between (1) perennial reference sites (representing target conditions for restoration), (2) non-perennial reference sites, (3) Three Links Farm restoration sites, and (4) H&E Farm restoration sites. Differences were analyzed with t tests using the Bonferroni adjustment for pair-wise comparisons, after log-transforming data (where necessary) to better approximate a normal distribution. For data that could not be normalized, non-parametric pair-wise comparisons were conducted using Wilcox Rank Sum tests with a Bonferroni adjustment. These statistical analyses were conducted using SAS v. 9.1 (SAS Institute 2007). To examine temporal changes, we compared the restoration sites individually to the perennial reference sites by expressing restoration site metrics as a proportion of the mean perennial reference site value by year.

Plant community composition was analyzed with non-metric multidimensional scaling (NMDS) based on Bray-Curtis distance (Kruskal 1964) using plant frequency data (i.e. percentage of plots occupied by a species during each year) for the 167 species encountered along the active channel during the study period. We used a random starting configuration and autopilot mode following the methods of McCune and Grace (2002). Using this same dataset, cluster analysis was used to identify site groups, based on Bray-Curtis distance, using the flexible beta coefficient linkage method (beta = .25). Indicator species analysis (Dufrene and Legendre 1997) was used to identify species associated with the site groups identified in the cluster analysis. Significance of species indicator values was assessed with Monte Carlo tests, using 1000 iterations. Multivariate analyses were conducted with PC-ORD v. 5 (McCune and Mefford 1999).

Analysis: Floodplain woody data

The vegetation community of each patch was categorized using a rule-based physiognomic-floristic hierarchical classification system (Grossman et al. 1998, Lite 2003, Bagstad et al. 2006). Vegetation classes included forest (canopy layer volume >60%), woodland (canopy volume 25-60%), shrubland (canopy volume <25%, midstratum volume >25%), grass- or forbland (canopy and mid-stratum volume <25%, groundcover >25%), and open (canopy volume in all three strata <25%). These classes were further defined according to composition and stem size of the dominant woody species following Bagstad et al. 2006. Bagstad et al. (2006) defined twelve common vegetation patch types for the San Pedro River – wet streamside, dry streamside, young cottonwood-willow, mature cottonwood-willow, old cottonwood, young tamarisk, mature tamarisk, wet (hydromesic) shrubland, mesquite patches, dry (xeric) shrubland, grassland, open patches. We assessed the relative area (% floodplain) of each patch type at each site for each sample year, and compared these percentages to examine change over time. Relative patch area was determined based on the average patch area for the two transects sampled at each site.

To facilitate inter-site and inter-year comparisons, woody vegetation structure variables (based on plot data) were reduced to the site (flood-plain) level. Percent of the flood-plain transect line occupied by each patch type was calculated for both transects per site, and these two values were averaged. The plot-level biomass structure values for a patch type were then weighted by the average width of the respective patch type at the site. In cases where there was >1 plot per patch, plot values were averaged at the patch level before patch type values were weighted. Plot level metrics included total and per species stem density (number of stems per hectare), and total and per species basal area (m^2 per hectare), total and per species vegetation volume, and species importance values. Importance values summarize the relative abundance of species, and may be used to determine community composition characteristics. Importance values were calculated using a modification of the Curtis and McIntosh (1951) formula: Importance value (IV) = (relative basal area + relative vegetation volume)/2. Importance values were calculated only for the three dominant pioneer tree species: *P. fremontii*, *S. gooddingii*, and *T. ramosissima.* Because *S. gooddingii* and *P. fremontii* are ecologically similar, their importance values were summed. Importance values were calculated at the site level.

To assess change in floodplain vegetation at each site with baseline data, we compared baseline (either 2000/2001 or 2002/2003) and current (2007/2008) vegetation patch structure and site-level vegetation metrics among four site groups (perennial reference sites, non-perennial reference sites, Three Links Farm restoration sites, and H&E Farm restoration sites). These statistical analyses will be conducted using either SAS v. 9.1 (SAS Institute 2007) or R.

III. RESULTS

A. Controlling Variables: Stream and groundwater hydrology

Pre-monsoon summer dry season surface flow presence varied among sites (Table 2). At Three Links Farm, May-June surface flow was present at the most upstream restoration site (3L2) in all years, an apparent shift from intermittent pre-restoration conditions. At 3L3, May-June surface flow was present at 50% of sampling dates (2004, 2005, and 2007). At the farthest downstream site (3L4) May-June surface flow was not present at any sampling date. At H&E Farm, May-June surface flow was not present at any site at any sampling date. At the wettest reference sites (TNCP, TNCI, 3LP), dry season surface flow was present in all years. At SHP, surface flow was present in 2003, but was absent thereafter due to channel aggradation. May-June surface flow was not observed at SHI or Narrows in any year.

Table 2. Pre-monsoon summer dry season surface flow status at lower San Pedro River restoration sites (n = 6 sample years, 2003-2008)

	Flow present (years)	Flow absent (years)
Three Links Farm		
3L2	6	0
3L3	3	3
3L4	0	6
H&E Farm		
HE1	0	6
HE2	0	6
HE3	0	6

Patterns of groundwater level recovery differed between the two farms (Figure 5). Groundwater levels showed a gradual increase during the study period at Three Links Farm. At 3L2, groundwater levels in a well located on the river terrace were within 1 m of the thalweg elevation (based on assumption of a horizontal water table). Groundwater levels in terrace wells were 3-5 m below the thalweg at sites 3L3 and 3L4, with a gradual 1-2 m rise following monsoon flooding in 2006 (Figure 5, top). At H&E Farm, groundwater levels declined slightly during the first four years of the study, and then rose 2-3 m following monsoon flooding in 2006 to within 1-2 m of the thalweg elevation (Figure 5, bottom).

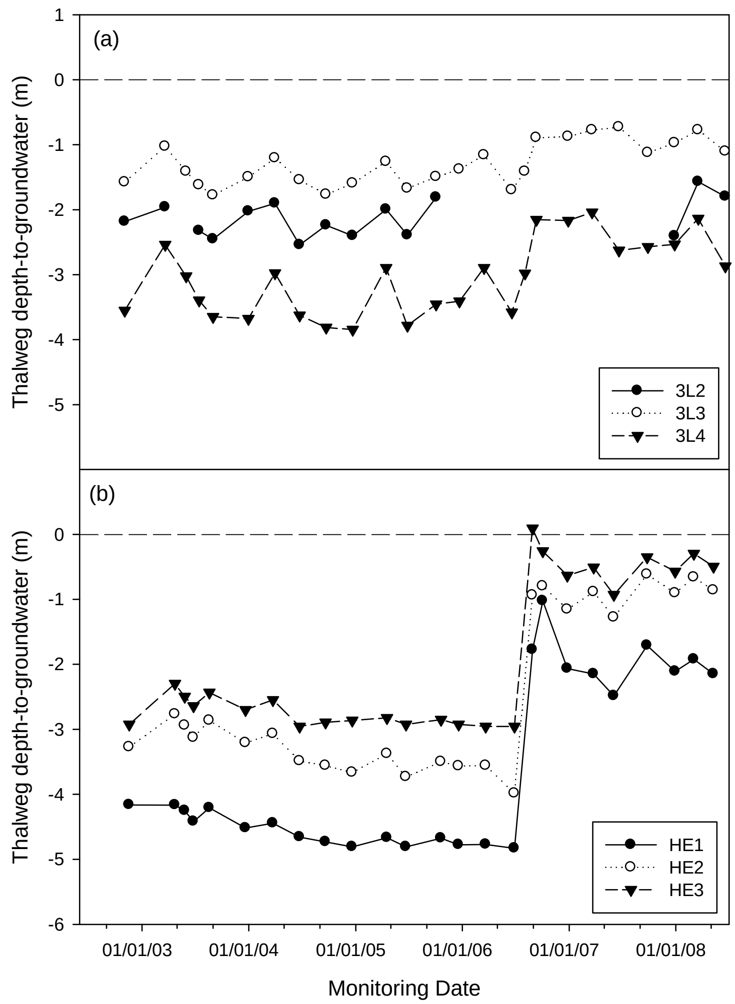

Figure 5. Depth to groundwater(m) below the active channel thalweg at LSPR restoration sites. (a) Three Links Farm. Data are derived from retired terrace irrigation wells 100-500 m from the channel. For 3L2, there are gaps in the monitoring record. (b) H&E Farm. Data are from floodplain piezometers within 50 m of the channel.

B. Short-term indicators: Streamside herbaceous vegetation

Target conditions. Several vegetation metrics differed between perennial and non-perennial reference sites. Streamside herbaceous cover and species richness were greater at perennial than at non-perennial reference sites (Table 3). Relative cover of both hydric perennials and hydric annuals was higher at perennial sites, while relative cover of mesic perennials and xeric annuals was higher at non-perennial sites (Table 3). Average weighted wetland indicator score (WIS) at perennial reference sites was significantly lower than at the non-perennial reference sites (Table 3). Streamside herbaceous cover tended to be dominated by non-native species at all sites, and was not significantly different between perennial and non-perennial reference sites (Table 3). Average streamside woody cover was not significantly different between perennial and non-perennial reference sites (Table 3).

Table 3. Mean (SE) streamside herbaceous vegetation characteristics of four site groups, all years combined.

	Target conditions: Perennial reference sites	Non-perennial reference sites	Three Links Farm restoration sites	H&E Farm restoration sites
Total cover %	39(3.6)	**22(5.3)**	43(6.0)	**11(2.8)**
Wetland indicator score	2.39(0.12)	**3.62(0.12)**	2.71(0.11)	**4.04(0.04)**
Species richness (m^2)	3.73(0.21)	**2.22(0.28)**	3.74(0.34)	**1.75(0.29)**
Non-native relative cover	0.64(0.03)	0.71(0.05)	**0.81(0.03)**	0.73(0.03)
Hydric perennial relative cover	0.28(0.04)	**0.01(0.00)**	**0.09(0.02)**	**0.00(0.00)**
Hydric annual relative cover	0.36(0.04)	**0.17(0.04)**	**0.50(0.03)**	**0.05(0.01)**
Mesic perennial relative cover	0.20(0.03)	**0.50(0.08)**	0.30(0.04)	**0.43(0.05)**
Mesic annual relative cover	0.13(0.04)	0.14(0.04)	0.05(0.01)	**0.29(0.05)**
Xeric perennial relative cover	0.01(0.00)	0.02(0.01)	0.01(0.00)	**0.04(0.01)**
Xeric annual relative cover	0.02(0.01)	**0.15(0.04)**	0.04(0.01)	**0.18(0.03)**
Woody cover %	35(3.5)	27(8.4)	22(5.3)	**13(2.3)**

Bold indicates a significant difference between site group and target conditions according to pair-wise t tests (cover, WIS, richness) or non-parametric paired Wilcoxon two-sample tests (relative cover metrics), alpha modified with Bonferroni adjustment. Sample sizes for herbaceous metrics are: perennial reference sites n=19, non-perennial reference sites n = 15, Three Links Farm restoration sites n = 18, H&E Farm restoration sites n= 18. Sample sizes for woody cover are: perennial reference sites n=4, non-perennial reference sites n = 4, Three Links Farm restoration sites n = 6, H&E Farm restoration sites n= 6. Sites SHP and TNCI were excluded from the woody cover metric due to recent changes in hydrologic status.

Restoration site conditions: synthetic community metrics. For all years combined, vegetation metrics were similar between Three Links Farm and the perennial reference sites (Table 3). Mean total cover, species richness and WIS at the Three Links Farm restoration sites were not significantly different from values at perennial reference sites. Relative cover of non-native species and hydric annuals was higher at Three Links Farm that at the perennial reference sites, as was cover of non-native species. Relative cover of hydric perennials was lower (Table 3). Examination of temporal trends suggests that relative cover of hydric perennials increased at the perennial reference sites during the study period (Table 4). This did not occur at the Three Links Farm restoration sites which instead tended to have high relative cover of hydric annuals and mesic perennials in all years. Generally, the Three Links Farm restoration sites had high species richness and cover during 2003-2005, but values were more similar to target conditions in 2006-2008 (Figure 6). This pattern of high cover was driven largely by site 3L2 (Figure 7), which was characterized by a unique combination of perennial streamflow and low levels of canopy cover (17% of target site woody cover). Streamside canopy cover was 80% of target cover at 3L3, and 83% at 3L4.

For all years combined, vegetation metrics tended to differ between the H&E Farm restoration sites and the perennial reference sites (Table 3). Mean total cover and species richness at the H&E farm restoration sites were significantly lower than at perennial reference sites, while mean WIS was significantly higher (indicating lower abundance of wetland species). Relative cover of non-native species did not differ between H&E farm and the perennial reference sites. Relative cover of all plant functional groups differed between H&E Farm and target conditions, as did streamside woody cover (Table 3). None of the vegetation metrics converged towards reference conditions over the course of the study (Figure 6 & 7). Streamside woody cover was 45% of target conditions at HE1, 22% at HE2, and 47% at HE3.

Table 4. Temporal changes in mean proportional cover of plant functional groups at reference and restoration sites.

	2003	2004	2005	2006	2007	2008
Perennial reference sites (n = 3, except 2003 n = 4)						
Relative cover						
Hydric perennials	0.11	0.11	0.28	0.42	0.37	0.43
Hydric annuals	0.29	0.43	0.27	0.27	0.49	0.38
Mesic perennials	0.23	0.17	0.28	0.28	0.08	0.12
Mesic annuals	0.29	0.23	0.09	0.03	0.05	0.04
Xeric perennials	0.01	0.00	0.03	0.00	0.00	0.00
Xeric annuals	0.03	0.05	0.03	0.01	0.00	0.00
Non-perennial reference sites (2003 n = 1, 2004 n = 2, 2005-2008 n = 3)						
Relative cover						
Hydric perennials	0.00	0.04	0.01	0.00	0.00	0.01
Hydric annuals	0.08	0.19	0.13	0.04	0.25	0.26
Mesic perennials	0.45	0.38	0.38	0.89	0.40	0.45
Mesic annuals	0.10	0.31	0.20	0.00	0.11	0.17
Xeric perennials	0.16	0.01	0.01	0.00	0.01	0.00
Xeric annuals	0.12	0.08	0.27	0.07	0.21	0.11
Three Links Farm restoration sites (n=3)						
Relative cover						
Hydric perennials	0.02	0.02	0.21	0.12	0.15	0.06
Hydric annuals	0.51	0.30	0.46	0.41	0.68	0.56
Mesic perennials	0.36	0.46	0.22	0.42	0.09	0.29
Mesic annuals	0.06	0.11	0.04	0.02	0.06	0.04
Xeric perennials	0.00	0.01	0.01	0.00	0.02	0.01
Xeric annuals	0.05	0.05	0.06	0.02	0.01	0.03
H&E Farm restoration sites (n = 3)						
Relative cover						
Hydric perennials	0.00	0.00	0.00	0.00	0.00	0.00
Hydric annuals	0.00	0.00	0.15	0.00	0.06	0.06
Mesic perennials	0.47	0.43	0.28	0.63	0.40	0.37
Mesic annuals	0.25	0.41	0.13	0.20	0.28	0.44
Xeric perennials	0.06	0.01	0.01	0.00	0.12	0.03
Xeric annuals	0.18	0.12	0.39	0.17	0.14	0.10

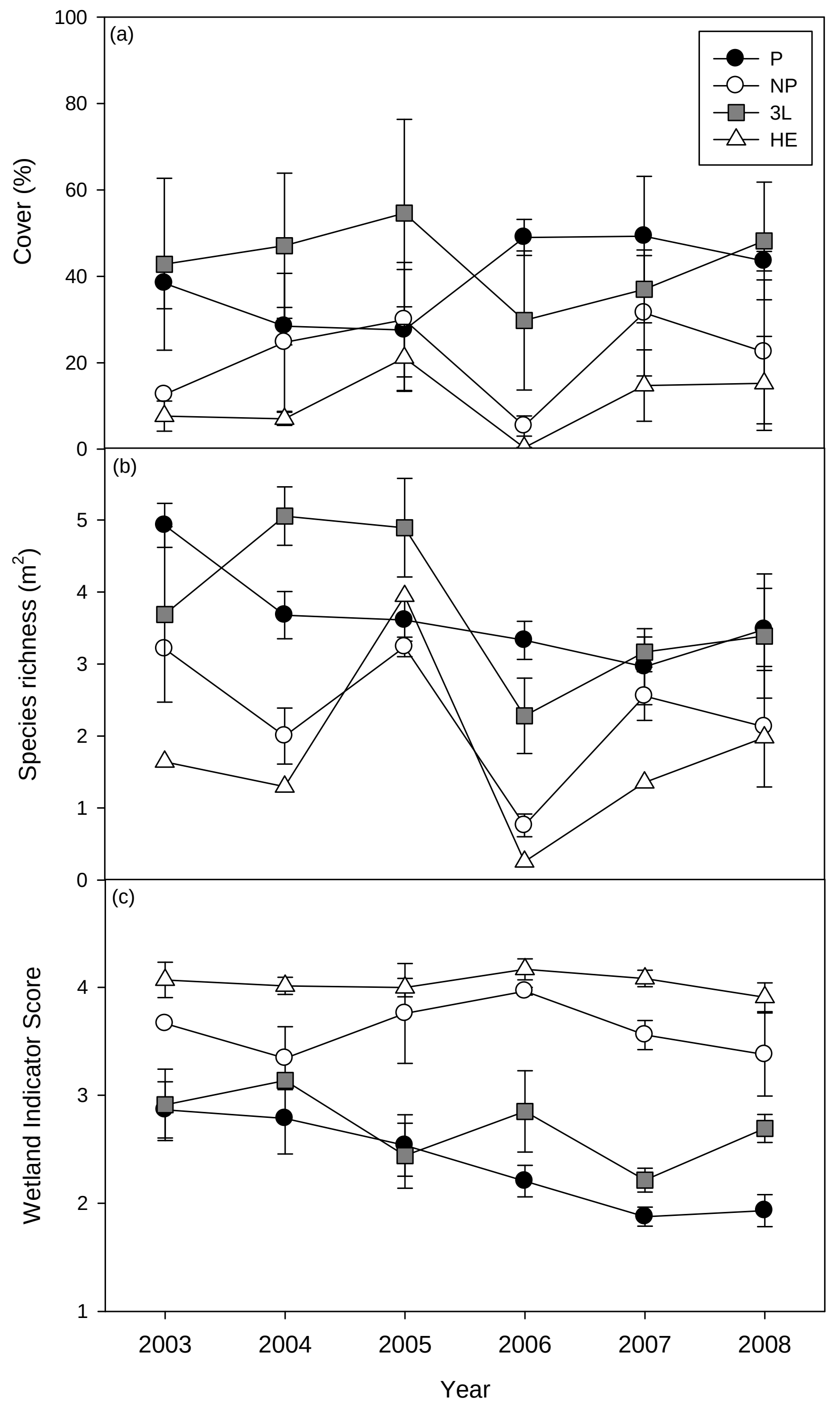

Figure 6. Characteristics (mean + SE) of reference and restoration site groups for each year of the study. P: perennial reference sites, NP: non-perennial reference sites, 3L: Three Links Farm restoration sites, HE: H&E Farm restoration sites. Sample sizes as in Table 5. (a) Mean total percent cover of herbaceous species in streamside plots (m2). (b) Mean plant species richness in streamside plots (m2). (c) Mean weighted wetland indicator score (WIS) of streamside herbaceous vegetation.

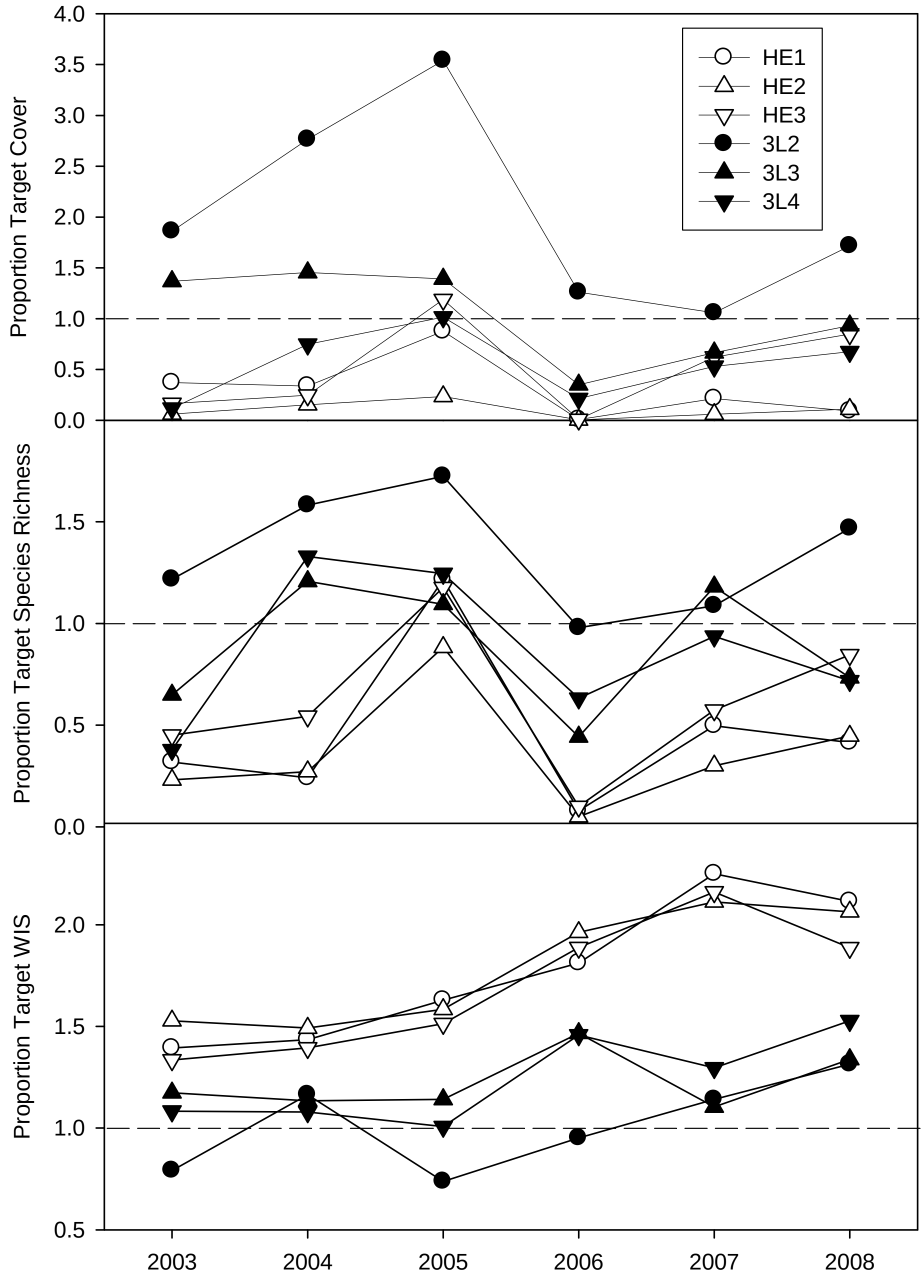

Figure 7. Vegetation structure at individual restoration sites expressed as a proportion of mean perennial reference site characteristics, by year. Dashed horizontal line indicates perennial site (target) conditions.

<u>Community composition: ordination</u>. NMDS ordination of all 69 site-year combinations (i.e., reference and restoration sites, 2003-2008) produced a 2-D solution (final stress = 16.65, final instability < 0.00001, Monte Carlo Test p = 0.004; Figure 8). The solution accounted for 84% of variability within the data set (Axis 1 = 60%, Axis 2 = 24%). Within the ordination space, sites were arranged according to hydrology, with perennial sites separated from non-perennial sites.

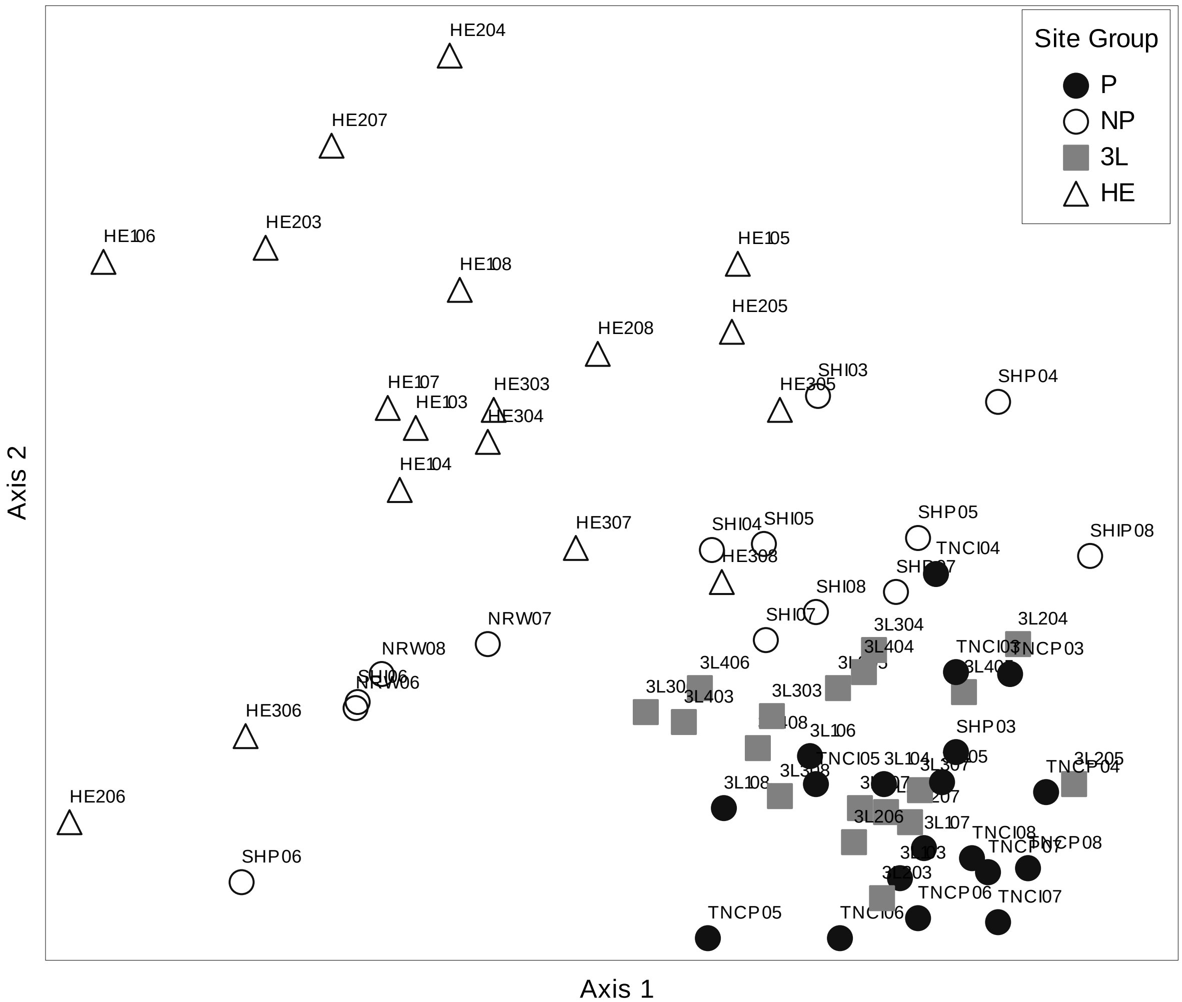

Figure 8. Streamside herbaceous plant community composition. Two-dimensional NMDS ordination of all 69 LSPR site-year combinations in species space, based on frequency of occurrence of 167 species in study plots. P: perennial reference sites, NP: non-perennial reference sites, 3L: Three Links Farm restoration sites, HE: H&E Farm restoration sites.

C. Long-term indicators: Floodplain geomorphology

When the 2008 surveyed floodplain cross sections are compared with baseline cross sections, several patterns are apparent. At Three Links Farm, floodplain cross sections appear to have remained stable during the study period, despite large monsoon floods in 2006 (Figure 9). In contrast, at H&E Farm geomorphic conditions have been more dynamic (Figure 10). In particular, at H&E Farm there appears to have been substantial channel rearrangement during the study period, with both erosion and deposition occurring within the active channel zone. At reference site TNCI, channel narrowing has occurred since the baseline survey was conducted (Figure 11). The geomorphic surveys at reference site TNCP suggest substantial channel downcutting and floodplain erosion during the study period (Figure 11).

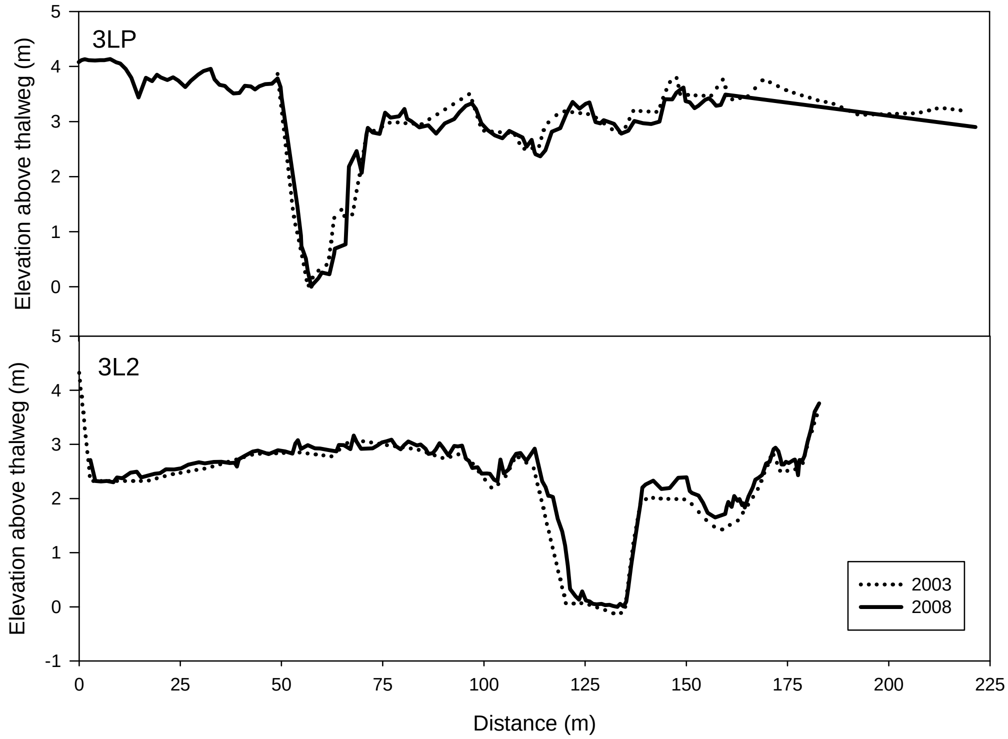

Figure 9. Floodplain cross sections surveys of two representative study sites at Three Links Farm. Site 3LP (upper panel) and site 3L2 (lower panel) in 2003 (dashed line) and 2008 (solid line).

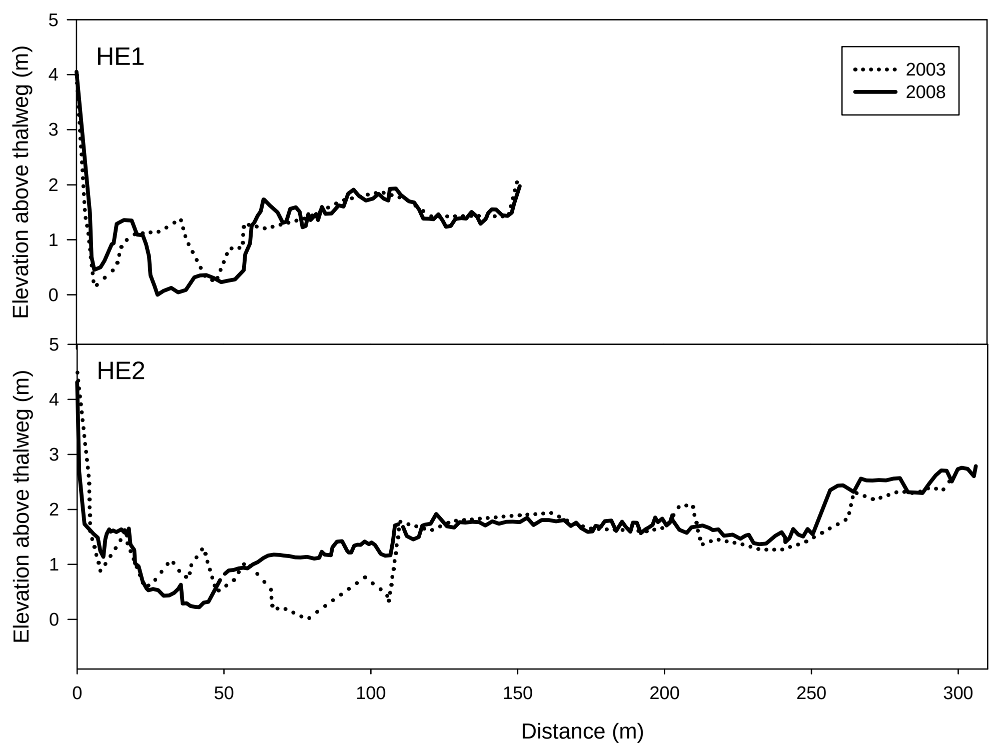

Figure 10. Floodplain cross sections surveys of two representative study sites at H&E Farm. Site HE1 (upper panel) and site HE2 (lower panel) in 2003 (dashed line) and 2008 (solid line).

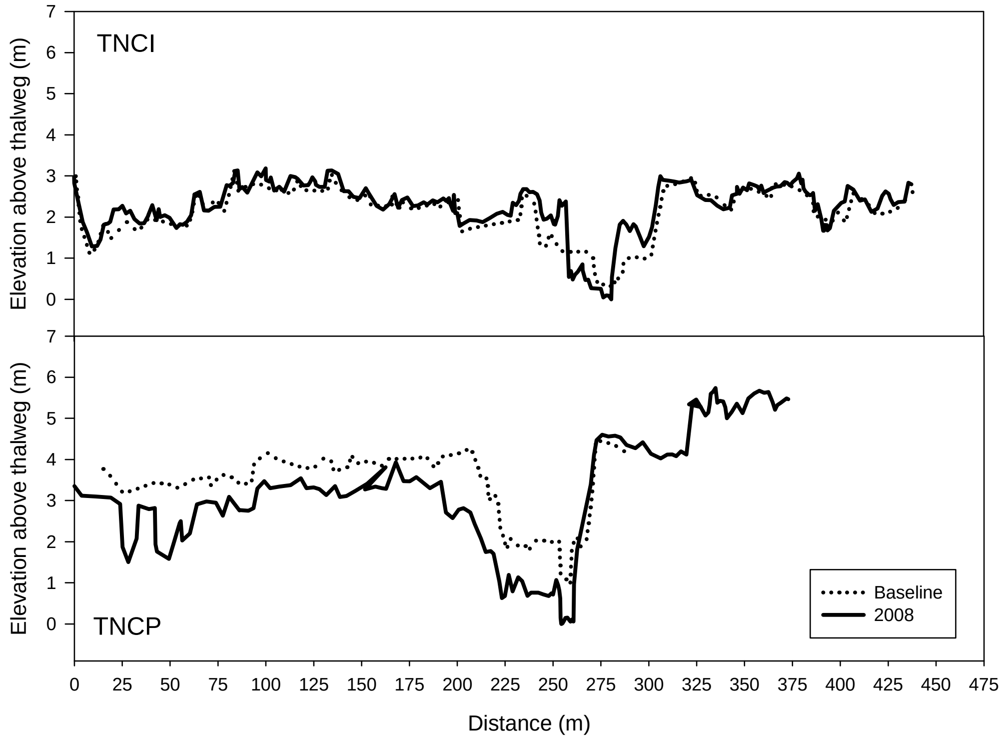

Figure 11. Floodplain cross sections surveys of two reference sites. TNCI (upper panel) and TNCP (lower panel) in 2001 (dashed line) and 2008 (solid line). The baseline survey was conducted for prior research (Lite, S.J. 2003).

D. Long-term indicators: Floodplain woody vegetation

Patch structure. The study sites differed markedly in terms of floodplain vegetation structure, and experienced contrasting patterns of change over time (Figures 12 and 13). In 2003, the restoration sites were dominated by open and shrubland patches, with very low (or no) occurrence of forest and woodland. In contrast, wetter sites had a greater floodplain proportion of forest and woodland. In 2007-8, the floodplain proportion of forest and woodland had increased slightly at the restoration sites, compared to baseline conditions. Increases in floodplain proportion of forest and woodland were 0.1-0.5 at the restoration sites (Figure 13). In contrast, floodplain proportion of forest and woodland decreased at most reference sites (Figures 12 and 13).

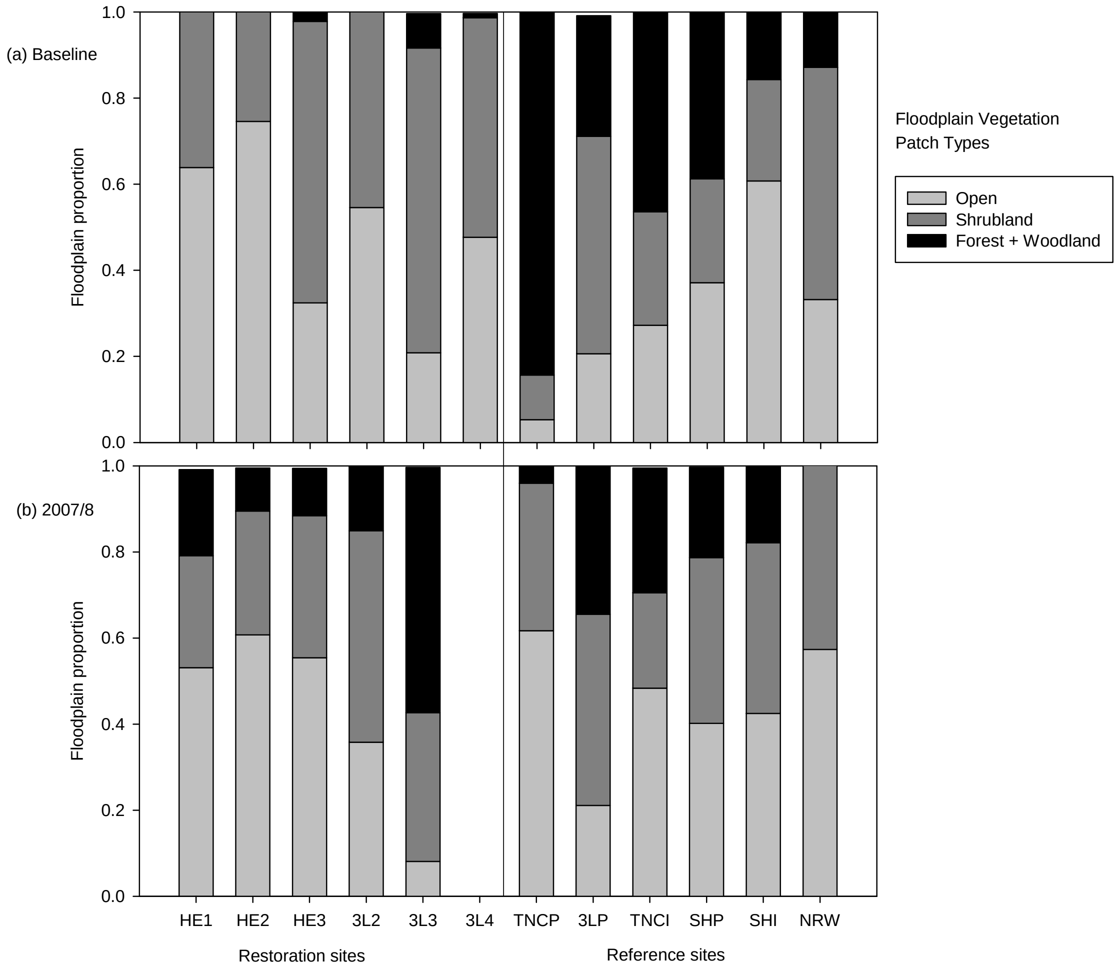

Figure 12. Floodplain woody vegetation patch structure at San Pedro River long-term monitoring study sites. (a) Baseline conditions (either 2000/2001 or 2003). (b) 2007/2008. Patch types have been simplified into three classes – Open (woody canopy volume in all strata <25%, herbaceous volume not assessed), Shrubland (canopy volume <25%, midstratum volume >25%), Forest + Woodland (canopy layer volume >60 or 25-60%). Note that perennial flow reference site TNCP was burned by wildfire in 2005, reducing the extent of cottonwood-willow forest on the floodplain. Site 3L4 could not be sampled in 2007/8 due to lack of access permission.

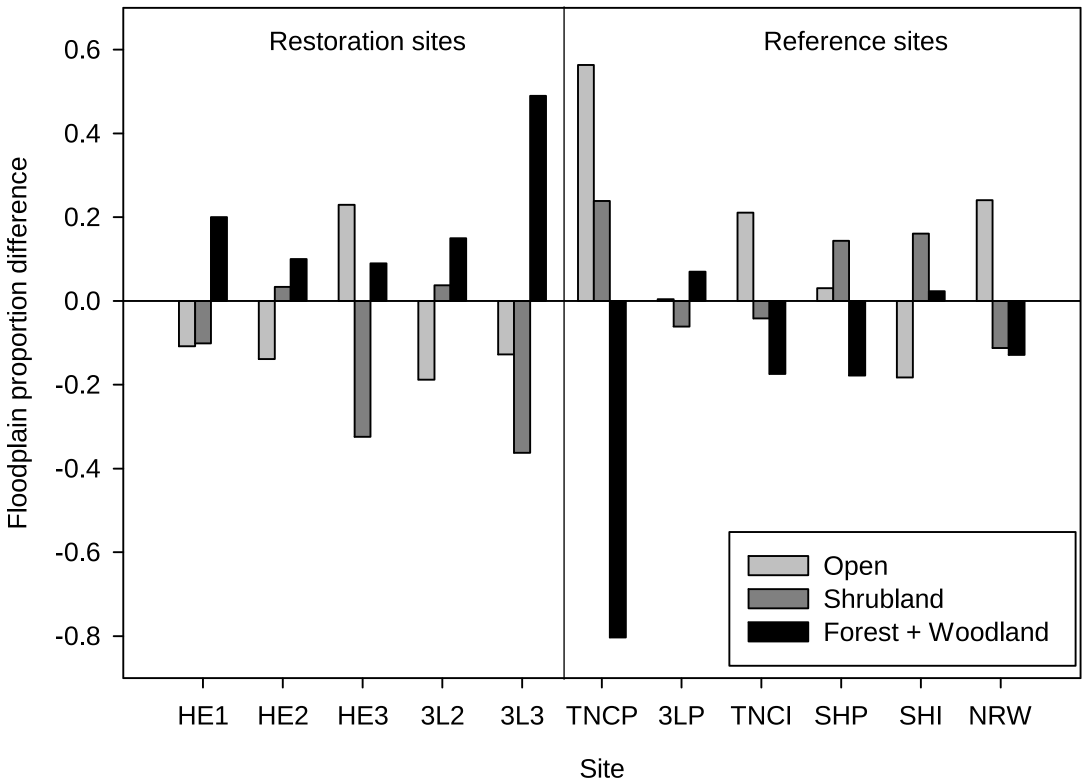

Figure 13. Difference in floodplain woody vegetation patch structure at San Pedro River long-term monitoring study sites, 2007/8 vs. baseline conditions. Positive values indicate an increase, and negative values indicate a decrease, in floodplain proportion between baseline data year and 2007/8. Patch types have been simplified into three classes – Open (woody canopy volume in all strata <25%, herbaceous volume not assessed), Shrubland (canopy volume <25%, midstratum volume >25%), Forest + Woodland (canopy layer volume >60 or 25-60%). Note that perennial flow reference site TNCP was burned by wildfire in 2005, dramatically reducing the extent of cottonwood-willow forest on the floodplain.

When combining physiognomic patch structure with species compositional differences among patches (Bagstad et al. 2006), similar patterns were detected. At Three Links farm changes in floodplain patch structure were minor (Figure 14). Site 3LP experienced very little change in patch structure between 2003 and 2007. In contrast, at site 3L2 Open and Young tamarisk patch areas decreased, while Mature tamarisk increased during the study period. Patch structure at 3L3 was very similar in 2003 and 2007. At H&E Farm slight changes in floodplain vegetation structure were observed over the course of the study (Figure 15). At site HE1, the amount Open patch area decreased, while Dry shrubland increased. Dry shrubland also increased between 2003 and 2007 at HE2. At site HE3 the amount of Open patch increased during the study period, while the area of mature tamarisk decreased. The patch structure at 3L4 was similar to that of 3L2 in 2003, being dominated by open and mature tamarisk patches. We were not able to re-sample site 3L4 in 2007/2008 but hope to do so at some time in the future. The new study site established in 2008, site 3L5, was dominated by open and mature tamarisk patches.

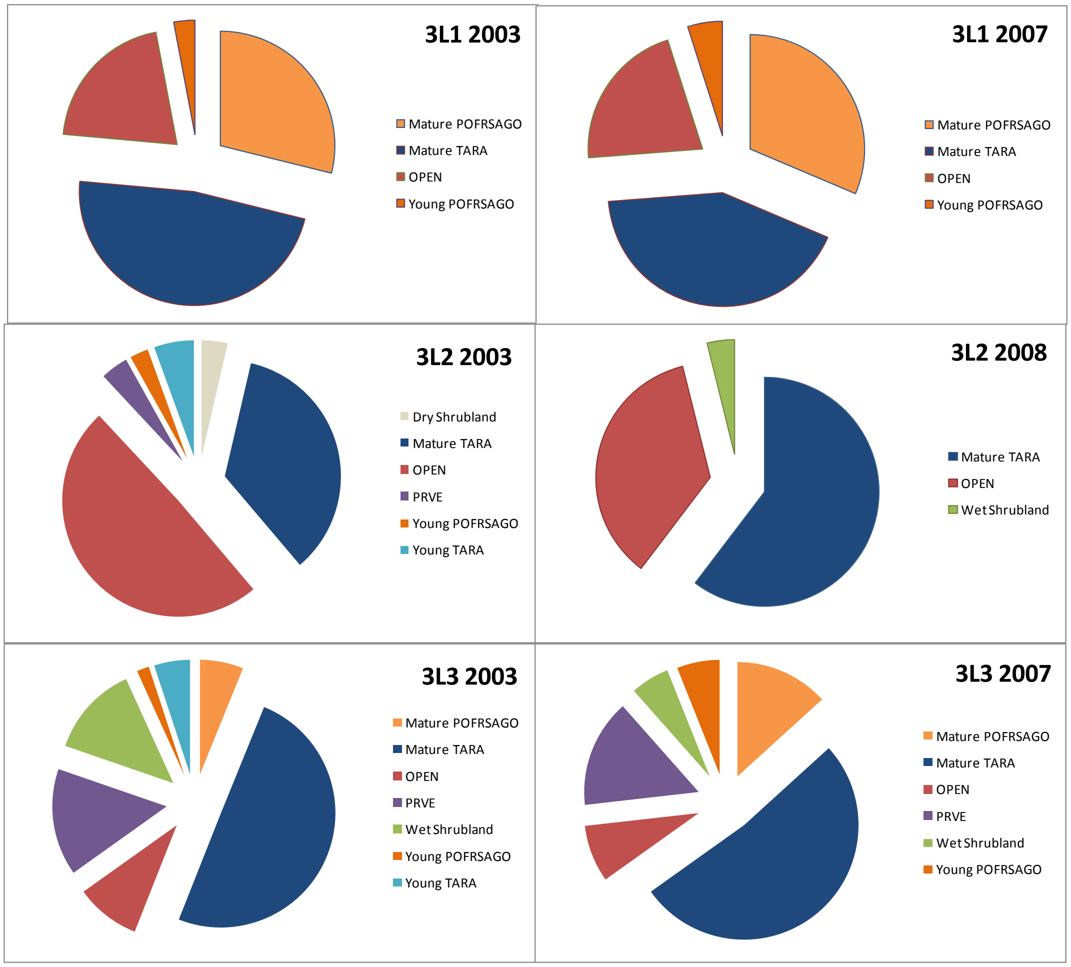

Figure 14. Three Links Farm floodplain patch type proportions in 2003 and 2007/2008. Top panel: 3LP, Second panel: 3L2, Third panel: 3L3, Lower panel left: 3L4 2003, Lower panel right: 3L5 2008. Note: Site 3L4 could not be re-sampled in 2007/2008 due to problems with site access. A new site (3L5) was established downstream of 3L4.

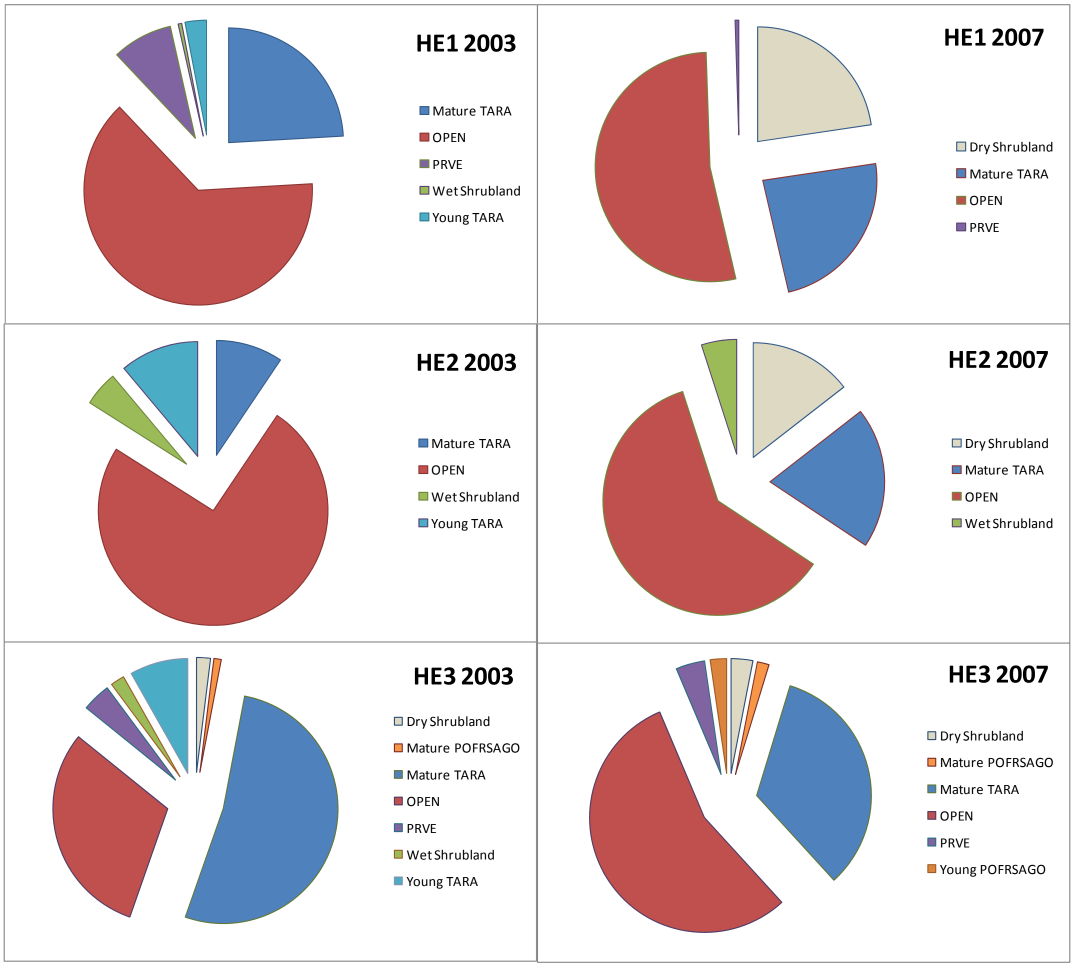

Figure 15. H&E Farm floodplain patch type proportions in 2003 and 2007. Top panel: HE1, Middle panel: HE2, Lower panel: HE3.

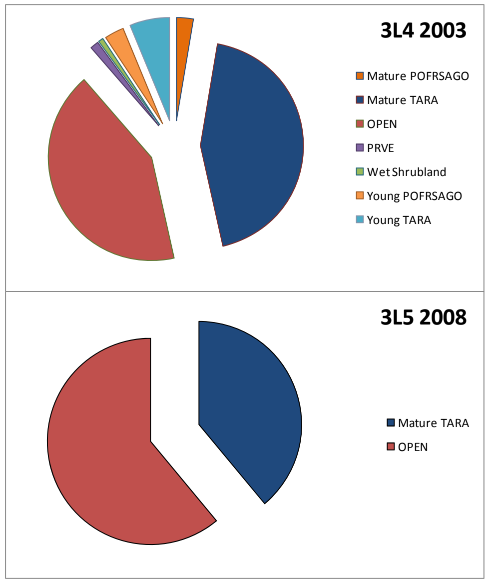

Figure 16. Three Links Farm floodplain patch type proportions for site 3L4 in 2003 and site 3L5 in 2008. Note: Site 3L4 could not be re-sampled in 2007/2008 due to problems with site access. A new site (3L5) was established downstream of 3L4.

Total woody floodplain vegetation. Site-averaged total stem density, basal area, and vegetation volume varied among sites (Table 5). In general, wetter sites had greater amounts of woody floodplain vegetation, compared to drier sites. However, these site level values were influenced by floodplain width, as some sites supported dense patches of vegetation within a wide floodplain that also contained more open patches. Site SHP was typical of such conditions, as it supported dense cottonwood-willow patches near the active channel, but the wide floodplain also contained less vegetated areas (which reduced the values of site-averaged vegetation metrics). At H&E Farm, restoration sites tended to have low values for total woody basal area and vegetation volume, compared to wetter sites. In contrast, stem density was not substantially lower at H&E Farm restoration sites than at wetter sites. This was due in part to the abundance of the multi-stemmed shrub *Hymenoclea monogyra*as, well as to the abundance of tamarisk, at H&E Farm sites.

The study sites appeared to experience distinctive changes in total woody vegetation density, basal area and vegetation volume between the two sample dates (Table 5). Overall, the restoration sites tended to have similar total vegetation structure at the two sample dates. One exception to this was the pronounced increase in stem density at HE3. Most reference sites had lower stem density in 2007/8 compared to baseline conditions, with the notable exception of SHI. Most reference sites had lower basal area in 2007/8 compared to baseline conditions, except SHI and NRW. Vegetation volume decreased at all reference sites, except NRW.

Table 5. Woody vegetation summary metrics for lower San Pedro River long term study sites.

	Baseline			2007/8		
	Density (stems/ha)	Basal area (m^2/ha)	Vegetation volume (m^3/ha)	Density (stems/ha)	Basal area (m^2/ha)	Vegetation volume (m^3/ha)
Three Links Farm restoration sites						
3L2	12943	13	13624	10555	20	15368
3L3	8929	40	16589	8987	34	19822
3L4*	14193	12	16815	--	--	--
3L5	--	--	--	6601	12	12014
H&E Farm restoration sites						
HE1	7368	6	--	6481	2	4763
HE2	14559	8	--	13660	2	4365
HE3	7371	9	--	14206	6	4311
Reference sites						
3LP	7524	35	15980	5105	23	11419
TNCP	22572	28	26723	3145	13	8938
TNCI	22591	21	18566	4085	9	10370
SHP	19665	15	9919	10671	13	9145
SHI	13502	10	13151	31188	14	9347
NRWS	12563	24	3385	2299	34	6546

*Site 3L4 was not re-sampled. Site 3L5 was added in 2008. Vegetation volume data was not collected at H&E Farm in 2002/3.

Abundance and importance of floodplain pioneer species. Basal area of all three floodplain woody pioneer species (*Tamarix* spp., *P. fremontii*, *S. gooddingii*) was low at most restoration sites in 2003, compared to baseline values at reference sites (Figure 17a). Basal area of cottonwood and willow varied from .03 to 1.7 m^2/ha at the H&E Farm restoration sites in 2003, and from 1.05 to 3.1 m^2/ha at the Three Links Farm restoration sites. In contrast, baseline values for basal area of cottonwood and willow ranged from 0.8 m^2/ha (Narrows) to 24.8 m^2/ha (TNCP) at reference sites. Basal area of tamarisk ranged from 2.0 to 5.8 m^2/ha at the H&E Farm restoration sites in 2003, and from 6.4 to 32.6 m^2/ha at the Three Links Farm restoration sites. For comparison, baseline basal area of tamarisk varied from 1.9 m^2/ha (TNCP) to 22.7 m^2/ha (Narrows) at the reference sites.

In 2007/8, basal area of woody pioneer species had declined at reference sites (Figure 17b), compared to baseline conditions. In contrast, at the Three Links Farm restoration sites, basal area of pioneer species increased. At H&E Farm, changes in basal area of woody pioneer species were minor. Basal area of cottonwood and willow varied from 2.7 to 10.1 m^2/ha at the Three Links Farm restoration sites in 2007/8, and from 0 to 1.5 m^2/ha at the H&E Farm restoration sites. For comparison, basal area of cottonwood and willow varied from 0 m^2/ha (Narrows) to 11.1 m^2/ha (TNCP) at the reference sites in 2007/8. For tamarisk, basal area varied from 17 to 21.1 m^2/ha at the Three Links Farm restoration sites in 2007/8, and from 1.3 to 3.5 m^2/ha at the H&E Farm restoration sites. At reference sites basal area of tamarisk ranged from 1.7 m^2/ha (TNCP) to 19.2 m^2/ha (Narrows) in 2007/8.

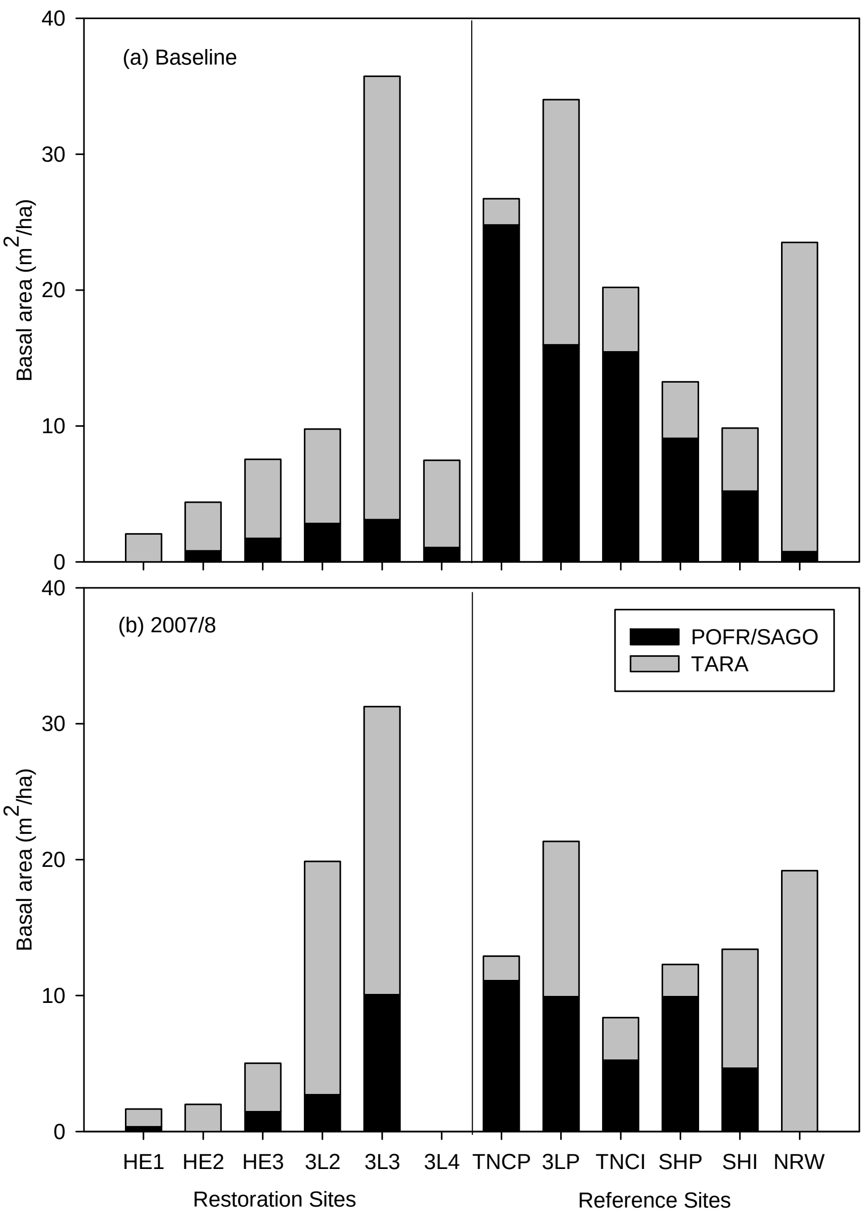

Figure 17. Basal area of floodplain woody pioneer species at San Pedro River long-term monitoring study sites. (a) Baseline conditions (either 2000/2001 or 2002/2003). (b) Conditions in 2007/2008. POFR/SAGO = combined basal area of *P. fremontii* and *S. gooddingii*, TARA = *Tamarix* spp. Site 3L4 could not be re-sampled in 2007/2008.

Relative basal area and vegetation volume of *Populus*-*Salix* and *Tamarix* differed among sites, and in many cases between sample dates (Tables 5 and 6). In general, wetter sites (e.g., TNCP, TNCI) supported greater relative basal area and vegetation volume of *Populus*-*Salix* than did drier sites (e.g., NRW). Comparing the two sample dates, at most sites relative basal area and vegetation volume of *Populus*-*Salix* tended to be lower in 2007/8 compared to baseline conditions. This was not observed at two of the H&E Farm restoration sites (HE1 and HE3), however, which had slightly higher relative basal area of *Populus*-*Salix* in 2007/8 compared to baseline values. Importance values (IV), calculated as the average of relative basal area and relative vegetation volume, showed similar patterns (Table 8). In general, IV of *Populus-Salix* tended to be lower in 2007/8 compared to baseline conditions, and was lower at drier sites compared to wetter sites. In turn, IV of *Tamarix* was generally higher in 2007/8 compared to baseline conditions, and was also higher at drier sites compared to wetter sites.

Table 6. Relative basal area of *Populus-Salix* and *Tamarix* at lower San Pedro River long term study sites.

	Baseline		2007/8	
	Populus-Salix	*Tamarix*	*Populus-Salix*	*Tamarix*
Three Links Farm restoration sites				
3L2	0.29	0.71	0.14	0.86
3L3	0.09	0.91	0.32	0.68
3L4*	0.14	0.86	--	--
3L5	--	--	0.05	0.95
H&E Farm restoration sites				
HE1	0.02	0.98	0.20	0.80
HE2	0.18	0.82	0	1
HE3	0.23	0.77	0.30	0.70
Reference Sites				
3LP	0.47	0.53	0.47	0.53
TNCP	0.93	0.07	0.86	0.14
TNCI	0.76	0.24	0.63	0.37
SHP	0.69	0.31	0.81	0.19
SHI	0.53	0.47	0.35	0.65
NRW	0.03	0.97	0	1

*Site 3L4 was not re-sampled. Site 3L5 was added in 2008.

Table 7. Relative vegetation volume of *Populus-Salix* and *Tamarix* at lower San Pedro River long term study sites.

	Baseline		2007/8	
	Populus-Salix	*Tamarix*	*Populus-Salix*	*Tamarix*
Three Links Farm restoration sites				
3L2	0.37	0.63	0.03	0.97
3L3	0.21	0.79	0.77	0.23
3L4*	0.25	0.75	--	--
3L5	--	--	0.02	0.98
H&E Farm restoration sites				
HE1	--	--	0.00	1.00
HE2	--	--	0.00	1.00
HE3	--	--	0.18	0.82
Reference Sites				
3LP	0.52	0.48	0.19	0.81
TNCP	0.84	0.16	0.91	0.09
TNCI	0.69	0.31	0.67	0.33
SHP	0.72	0.28	0.57	0.43
SHI	0.47	0.53	0.33	0.67
NRW	0.00	1.00	0.00	1.00

*Site 3L4 was not re-sampled. Site 3L5 was added in 2008. Vegetation volume was not sampled at H&E Farm in 2002/3.

Table 8. Importance Value (IV) of *Populus-Salix* and *Tamarix* at lower San Pedro River long term study sites.

	Baseline		2007/8	
	Populus-Salix	*Tamarix*	*Populus-Salix*	*Tamarix*
Three Links Farm restoration sites				
3L2	0.33	0.67	0.08	0.92
3L3	0.15	0.85	0.55	0.45
3L4*	0.19	0.81	--	--
3L5	--	--	0.04	0.96
H&E Farm restoration sites				
HE1	--	--	0.10	0.90
HE2	--	--	0.00	1.00
HE3	--	--	0.24	0.76
Reference Sites				
3LP	0.49	0.51	0.33	0.67
TNCP	0.89	0.11	0.89	0.11
TNCI	0.73	0.27	0.65	0.35
SHP	0.71	0.29	0.69	0.31
SHI	0.50	0.50	0.34	0.66
NRW	0.02	0.98	0.00	1.00

*Site 3L4 was not re-sampled. Site 3L5 was added in 2008. Importance values calculated as IV = (relative basal area + relative vegetation volume)/2. Vegetation volume was not sampled at H&E Farm in 2002/3, so IV not calculated.

Cottonwood-willow size classes. The number of size classes of cottonwood and willow was generally higher at wetter sites, with baseline values ranging from 5 to 8 at perennial flow reference sites (Table 9). The number of size classes was lower at the restoration sites, ranging from 0 to 4 in 2003. Over time, the number of size classes appeared to decrease at all sites except HE1.

Table 9. Number of *Populus fremontii – Salix gooddingii* 10cm diameter size classes at lower San Pedro River study sites.

	Baseline	2007/8
Three Links Farm		
3L2	3	1
3L3	4	3
3L4	3	NA
H&E Farm		
HE1	1	2
HE2	2	0
HE3	0	0
Perennial flow reference sites		
TNCP	7	4
3LP	5	5
TNCI	7	5
SHP	8	6
Non-perennial flow reference sites		
NRW	1	0
SHI	7	3

IV. Discussion

A. Short term indicators: Streamside plant communities

Influence of hydrology and other environmental factors

This study confirmed that surface flow hydrology is a key factor shaping the LSPR streamside plant communities, as revealed by the NMDS ordination and by contrasts of synthetic community metrics between perennial and non-perennial reference sites. It also revealed the influence of other factors. Of note, tree canopy cover emerged as a correlate of streamside herbaceous plant species composition. Many perennial-flow sites have dense growth of broad-leaved trees along a well defined and narrow active channel, in contrast to dry sites that often have less well defined channels and less tree cover. Tree growth near the channel may shape understory communities through various mechanisms including temperature moderation, shading, substrate stabilization, litter inputs and uptake of nutrients (Corenblit et al. 2007; Follstad Shah & Dahm 2008).

Measures of restoration success: target conditions

Perennial-flow reference sites had higher herbaceous cover, higher species richness, lower weighted wetland indicator scores, and higher relative cover of hydric perennials and hydric annuals than non-perennial sites. In contrast, non-perennial sites had higher relative cover of mesic perennials and xeric annuals. These finding are consistent with those of Stromberg et al. (2005) who found herbaceous cover, richness and wetland indicator score to be correlated with annual flow permanence on the San Pedro River, and described the shift from perennial to non-perennial flow as a critical threshold, involving loss of perennial hydric herbs. All of these are useful metrics for assessing riparian condition.

An additional plant community trait that emerged as a useful metric for assessing restoration success was the degree of year to year variability in plant community composition. The perennial-flow sites were characterized by high constancy of plant species across time and space (Figure 7). In contrast, the non-perennial sites were more dispersed within the ordination space, and individual sites showed considerably more year-to-year variability in species composition (Appendix 1). Similarly, perennial flow sites exhibited less year-to-year variability in plant cover and species richness than non-perennial sites.

Dominance by native species is often stated as a measure of restoration success (e.g., Harris 1999; Trowbridge 2007). In this study, average relative cover of non-native species was high, on the order of 70%, and did not differ between perennial and non-perennial reference sites (Table 2). In some hydrologically altered riparian systems, increased native dominance might indicate the return of physical conditions to which the species are adapted, a phenomenon that has been observed for woody species in some settings (Sher et al. 2002). On the other hand, stream intermittency is not unusual in desert riparian systems, and therefore dry conditions are not necessarily expected to favor non-native herbaceous species over natives. Thus, dominance by native herbs per se is not a measure of hydrologic restoration in this system. We speculate that non-native species dominance may reflect the degree of present or recent agricultural activity (i.e., livestock grazing, irrigated crops) at a site, possibly through enhanced propagule and nutrient inputs. Non-native dominance may also reflect disturbance level, since there is a greater proportion of non-natives among the annuals than among the perennials of the San Pedro flora (Stromberg et al. 2009).

Assessment of restoration success

With conditions at perennial reference sites defined as the target for restoration, our data indicate that restoration goals for the streamside herbaceous community have largely been achieved at Three Links Farm, but not at H&E Farm. According to most measures, Three Links Farm supported vegetation similar in structure and composition to that of the perennial reference sites. Mean streamside herbaceous plant cover, species richness, WIS, and relative cover of most plant functional groups were similar to target conditions, though Three Links farm supported higher relative cover of non-native species and of hydric annuals. The prevalence of hydric annuals may be a legacy of disturbance history (e.g., periodic drought/flow intermittency, floods, or grazing). Continued monitoring will be needed to determine whether hydric annuals will be replaced by hydric perennials at this site in response to the shift towards more permanent water availability. Three Links Farm restoration sites grouped with the perennial reference sites compositionally, as indicated by ordination results and cluster analysis.

Figure 18. Site 3L2 in 2003. Note high streamside herbaceous cover dominated by the non-native annual grass *Polypogon monspeliensis*, and little streamside shade.

Figure 19. Site HE3 in 2003. Note the wide dry channel with low streamside herbaceous cover and little shade.

In some cases restoration site metrics were higher than target conditions. In particular, 3L2 had high herbaceous cover and species richness (Figure 7), likely due to its combination of shallow groundwater, high surface flow permanence, and low levels of streamside woody cover. This pattern of high resource availability in restored wetlands producing anomalous outcomes has been observed elsewhere. For example, re-wetted degraded peat meadows had higher plot-level species richness and distinct species composition compared to reference wetlands in the Netherlands, likely due to elevated nutrient levels (van Dijk et al. 2007). In the US, restored wetlands can have higher plant diversity than natural wetlands, possibly because wetland construction practices promote colonization (Kentula et al. 1993). Kentula et al. (1993) argued that restored wetlands initially may have higher function levels than reference wetlands and may approach reference levels over time. We anticipate that conditions a 3L1 may eventually change as woody species establish and grow along the channel, thereby reducing light levels and cover of the herbaceous understory.

Like many restoration projects, we do not have pre-restoration baseline data due to lack of site access prior to restoration. This leaves open the possibility that the Three Links Farm hydrology and streamside herbaceous plant community were not altered by historic groundwater pumping, and that interpretation of streamside conditions as 'recovery' is erroneous. However, assuming that the anecdotal evidence of historic non-perennial flow throughout much of Three Links Farm is valid, it appears that the streamside zone has indeed responded rapidly to the restoration project. This is plausible, since streamside plants can respond quickly to changed environmental conditions (e.g., to livestock removal, Krueper et al. 2003; or flooding, Stromberg et al. 1997).

In contrast, vegetation characteristics at the H&E Farm restoration sites were not similar to target conditions despite substantial recovery of groundwater levels. H&E Farm restoration sites had lower streamside plant cover, species richness, relative cover of hydric perennials, and hydric annuals, and higher WIS, relative cover of mesic perennials, and relative cover of xeric annuals than perennial reference sites. In the NMDS ordination, the H&E Farm restoration site-year combinations generally plotted beyond the range of variation of the reference sites, and did not tend to converge towards the species composition of reference sites over time. In the cluster analysis, the H&E Farm sites grouped separately from the perennial reference sites. Thus, according to the model depicted in Figure 8, H&E Farm streamside herbaceous vegetation persists in a degraded condition; no recovery thresholds have been crossed.

<u>Barriers to restoration success</u>

Stable state. One possible explanation for the lack detectable recovery at H&E Farm is that the current condition is stable and change in the expected direction will not occur. In this scenario, either no additional hydrologic recovery will take place, or such recovery will not produce the desired biotic results, and present conditions will persist indefinitely. This outcome could result from an incorrect understanding of historic site conditions (e.g., if the reach was always ephemeral due to geologic factors), or by the presence of unidentified restoration barriers or thresholds (Hobbs 2007). For example, aquifer storage capacity can be reduced due to compaction following groundwater pumping; this inelastic change can impair groundwater recharge (Bell et al. 2008). Recovery could be impeded by the existence of a self-reinforcing stable state at H&E Farm that is resilient to restoration-induced change (Suding et al 2004). Heffernan (2008) argued that riverine wetlands and bare gravel channel beds represented alternative stable states on Sycamore Creek, Arizona. In the latter case, lack of channel bed vegetation resulted in frequent mobilization of channel bed sediments in response to flooding, which in turn reinforced the un-vegetated state.

Hydrology, climate and spatial context. Alternatively, the hydrologic system at H&E Farm may be characterized by slow rates of change towards target conditions. In this scenario, incremental increases in groundwater levels will eventually cross the hydrologic thresholds required to drive vegetative shifts (Figure 8). Slow hydrologic recovery could result from intrinsically slow rates of groundwater recharge, and from the sheer magnitude of aquifer depletion. Groundwater pumping for irrigation occurred over many decades; it may be unreasonable to expect aquifer recovery to occur within years following cessation of pumping (Filippone & Leake 2005). Further, intrinsically slow hydrologic recovery may have been exacerbated by recent drought. The regional climate of the Southwest exhibits high inter-annual and multi-decadal variability (Pool 2005), and was characterized by drought beginning in 1999 and persisting throughout the study period (NOAA-NCDC 2008).

Hydrogeomorphic context may constrain restoration outcomes in this system, by influencing both rates of groundwater recharge and frequency of surface flow. Mountain system recharge, diffuse recharge, and ephemeral channel recharge all contribute to groundwater in the San Pedro River basin (Baillie et al. 2007; Wahi et al. 2008). Although mountain recharge may dominate semi-arid basins overall, on the Upper San Pedro River riparian groundwater on losing reaches can be dominated by monsoon flood-derived channel recharge (Baillie et al. 2007). Ephemeral channel recharge occurs in a pulsed fashion due to the episodic nature of flooding (Pool 2005). H&E Farm may typify such conditions, as evidenced by the increase in water table elevations after monsoon flooding in 2006. Thus, groundwater in this reach may eventually rise to levels typical of wet streamside vegetation patches elsewhere on the San Pedro River (0-1 m depth to groundwater, Bagstad et al. 2006).

Despite increases in groundwater levels, the location of H&E Farm in a lengthy dry river section far from upstream perennial surface water sources is an impediment to surface flow recovery. Surface flow at Redington occurs only in response to storm events, and is likely indicative of flow conditions at H&E Farm where we observed no dry season surface flow. Flow permanence at H&E farm is thus far below values typical of wet streamside vegetation patches on the San Pedro River (>70% annual flow permanence, Bagstad et al. 2006), or the perennial flow conditions required for maintenance of hydric perennial plant assemblages (Stromberg et al 2005). In contrast, the hydrogeomorphic location of Three Links Farm supports greater surface flow permanence. Monitoring data indicate that winter-spring surface flow extended throughout Three Links Farm in 2006-2008, including all restoration site locations (TNC, unpublished data). Surface flow permanence is promoted at the southern end of the farm by high connectivity between the riparian aquifer and the deeper basin-fill aquifer which supplies recharge by lateral and vertical inflow (Haney & Lombard 2005).

Biotic impediments. If hydrologic recovery does occur at H&E Farm, we speculate that biotic response to the changed physical conditions may be slower than at Three Links Farm because of their differing spatial contexts along the river. Perennial reaches of dryland rivers, including those in Arizona, contain diverse seed banks that provide propagules for restoration (Boudell & Stromberg 2008; Williams et al. 2008). However, the abundance and diversity of hydric species in the seed banks declines with distance downstream of a perennial reach (Stromberg et al. in press). Dispersal limitation influences patterns of riparian response to flow restoration in some contexts (e.g., floodplains in California, USA; Trowbridge 2007), and diaspore transfer has been shown to improve restoration outcomes (e.g., wet meadows in western Europe, Klimkowska et al. 2007). In our study, restoration sites at Three Links Farm were within 4 km of upstream perennial reaches that could serve as seed sources, while restoration sites at H&E Farm were ~17 km from the nearest upstream perennial reach. However, because the LSPR is undammed and characterized by a dynamic flood regime, longitudinal connectivity is fairly high in this system and dispersal limitation is unlikely to be a primary constraint of vegetation change.

B. Long term indicators: Woody floodplain vegetation

Influence of hydrology

Our results are generally consistent with prior research, in that many aspects of woody floodplain vegetation structure appear to differ among sites with contrasting hydrology. Previous research on the San Pedro River has indentified characteristics of woody floodplain vegetation indicative of site hydrology (Lite and Stromberg 2005, Lite et al. in review). Lite et al. (in review) developed a stressor-response model for San Pedro River riparian vegetation by testing the sensitivity of multiple response variables to site hydrology (surface flow permanence, groundwater depth, and groundwater fluctuation). They determined that five woody vegetation indicator variables were significantly affected by site hydrology: number of 10 cm *P. fremontii* and *S. gooddingii* size classes, *P. fremontii* and *S. gooddingii* basal area (m^2/ha), *P. fremontii* and *S. gooddingii* relative basal area (%, compared to *Tamarix* basal area), maximum vegetation height (m) on the floodplain, and percent of the floodplain occupied by Shrublands. For each of these variables except the last, higher values indicated wetter sites characterized by greater streamflow permanence, smaller depth to groundwater, and less annual groundwater level fluctuation. For floodplain proportion of Shrublands, higher values indicated drier sites. This model has been applied in the upper San Pedro River basin in order to assess the condition of river reaches within the San Pedro River National Conservation Area (Stromberg et al. 2006). In our study, drier sites did generally have lower *P. fremontii* and *S. gooddingii* basal area (m^2/ha), lower *P. fremontii* and *S. gooddingii* relative basal area, and fewer cottonwood and willow size classes.

Many stressor-response models and threshold models are developed under the assumption that site vegetation is in equilibrium with the environmental variables of interest. For example the models of Lite et al. (in review) and Lite and Stromberg (2005) were based on vegetation and environmental data collected at a large number of sites within a short period of time, and thus represent a "snap shot" of riparian conditions. These models assume that extant vegetation is in equilibrium with site hydrology. While this assumption is likely valid in many cases, it may not always hold true. For example, it is not known how long it will take for riparian vegetation to respond to changes in riparian hydrology. This may be especially true in semi-arid regions where vegetation and fluvial geomorphic change can be slow, and for relatively long-lived organisms such as trees which may exhibit a considerable lag time in their response to altered hydrology (Katz et. al 2005). Earlier work by Stromberg (1998) suggested that relative abundances of cottonwood-willow and tamarisk have changed through time along the lower San Pedro River. More recently, Stromberg et al. (2010) documented pronounced changes in geomorphology and vegetation structure on the upper San Pedro River, with floodplain vegetation increasing markedly over the past century in association with channel incision and narrowing. However, more detailed understanding of time-scales and rate of change, and the degree to which vegetation may exhibit a lag time in its response to hydrologic amelioration, is needed. Vegetation can exhibit 'inertia', with certain plant species continuing to remain dominant despite incremental changes in environmental factors such as groundwater level. Major environmental change, such as large flooding, may be required to bring about vegetation shifts and reverse historical vegetation changes.

Influence of other factors

Riparian ecosystems are dynamic systems influenced by a variety of factors in addition to groundwater levels and surface flow permanence. Woody floodplain vegetation structure was dynamic at all of the study sites, indicating that factors other than hydrology influence riparian conditions on the San Pedro River. In particular, all sites were affected by drought during most of the study period, punctuated by large monsoon floods in 2006. In addition, one site (TNCP) experienced a wildfire during the study. These factors may have contributed to the decline in basal area of woody pioneer trees and the loss of Forest and Woodland floodplain patch area at the reference sites during the study period. Drought related losses of woody vegetation have been observed elsewhere in the Southwest during the past decade. For example, recent regional drought has contributed to widespread mortality of upland trees, resulting in substantial changes to landscape scale vegetation patterns (Breshears et al. 2005, Breshears et al. 2009). Fire can also reduce woody vegetation abundance in riparian areas, at least in the short term. For example, riparian fire caused immediate declines in stem density and basal area of woody pioneer trees on the upper San Pedro River (Stromberg and Rychener

2010). It has been hypothesized that wildfire may have a homogenizing influence on floodplain vegetation, since fire impacts may not produce the zonation typical of fluvial disturbance (Bendix and Cowell 2009). Thus, multiple factors influenced the patterns of vegetation change observed at the reference sites during this study.

Figure 20. Site TNCP in 2006, approximately one year after wildfire. Former cottonwood forest patch, with dead cottonwood trees still standing and re-sprouting willow and tamarisk in the understory.

Figure 21. Site TNCP in 2007, two years after wildfire. Former cottonwood forest patch, with some bare stems of dead cottonwood still standing, and re-sprouting tamarisk in the understory.

Effects of hydrologic restoration.

According to some measures the hydrologic restoration experiment being conducted on the lower San Pedro River appears to have reversed the trends in long-term vegetation indicator conditions at restoration sites, compared to reference sites. In particular, reference sites tended to experience reduced floodplain area of forest and woodland, reduced basal area of cottonwood and willow, and reduced IV of cottonwood and willow, between the two sample dates. However, restoration sites experienced contrasting patterns of change. Restoration sites tended to experience increased floodplain proportion of forest and woodland, and increased basal area of cottonwood and willow, between the two sample dates. Further, declines in total floodplain woody stem density, basal area, and vegetation volume were generally more pronounced at reference sites than at restoration sites. Thus, although improvements in long term indicators of vegetation condition were subtle at restoration sites, they were nonetheless notable, especially when compared to trends at reference sites. These results suggest that even at sites affected by severe regional drought, cessation of groundwater pumping has been an effective approach to hydrologic restoration. We expect that as drought conditions ameliorate, the effects of this hydrologic restoration strategy will become increasingly evident.

V. Conclusion

In this study, we examined multiple response variables over a relatively long time period, and also compared restoration sites to reference sites, in order to assess the effects of hydrologic restoration on river and riparian conditions. This approach enabled us to describe trends in short term indicators of ecosystem response (e.g., streamside vegetation conditions), and patterns of change in long term indicators (e.g., woody floodplain vegetation structure). It also allowed us to compare the changes at restoration sites to those observed at reference sites, and thereby tease apart the role of the restoration treatment from the effects of other environmental influences in this dynamic riparian system.

On a single river, sites may respond differently to restoration treatments. Such divergent patterns may reflect differences among sites in the physical constraints on the riparian ecosystem. In this study, the contrasting patterns of short term riparian response to restoration -- with one case of apparent rapid hydrologic and vegetation response and another case of no detectable change after six years -- were likely due to differences in aquifer response to cessation of groundwater pumping as influenced by the hydrogeomorphic context. Understanding the constraints on restoration response is critical for setting realistic restoration goals and anticipating timeframes of ecosystem change.

Over time, sites are influenced by a variety of environmental factors. In the context of restoration, this underscores the importance of reference sites for interpreting patterns of vegetation change. The restoration sites in this study experienced subtle changes in woody floodplain vegetation structure over the course of this study. However, these changes contrasted strongly with those occurring at reference sites, which generally experienced reductions in basal area of woody pioneer species and loss of floodplain forest and woodland during the study period. Regional drought, flooding, and wildfire all likely contributed to these trends at reference sites. Although the restoration sites also experienced drought and flood, basal area of woody pioneer species and floodplain percentages of forest and woodland generally increased during the study period.

Our results indicate that hydrologic restoration holds great promise as a restoration technique on the San Pedro River, and perhaps along other arid region rivers as well. In particular, reduced groundwater pumping appears to have resulted in increased riparian water table elevations and improved surface flow permanence at some restoration sites. Because the San Pedro River is undammed, it experiences periodic monsoon floods which can recharge alluvial groundwater and provide the fluvial disturbance necessary for regeneration of riparian pioneer trees. However, riparian dynamics on the San Pedro River are influenced by other factors in addition to hydrology, and ultimately vegetation patterns at restoration sites will reflect the interacting influences of numerous conditions and processes. A long-term commitment to restoration projects and to restoration research is required to achieve a comprehensive understanding of these influences, and how they affect restoration success.

VI. Lessons learned

The overall goal of this project was to assess the effectiveness of a hydrologic-based approach to riparian ecosystem restoration on the lower San Pedro River. To this end, the study addressed three main research questions, which are briefly evaluated below.

- This project tested the idea that streamside wetland communities (of comparable composition and diversity to reference conditions) would develop as stream flows once again became perennial. This idea was confirmed, in that streamside herbaceous communities at the Three Links Farm restoration sites (the wettest restoration sites) were very similar to those of perennial reference sites.

- This project also tested the idea that shifts from *Tamarix* to *Populus-Salix* forests could be accomplished solely by modifying the hydrologic regime. Specifically, we hypothesized that during a five-year period (2003-2008) increased surface flow permanence and decreased depth-to-groundwater would promote dominance of *Populus-Salix* at restoration sites on the un-dammed San Pedro River. This idea was not strongly supported by our study -- Of the two wettest restoration sites for which we have data, one site (3L3) experienced an increase in floodplain proportion of forest and woodland and an increase in relative basal area of *Populus-Salix*. The other site (3L2) experienced a slight increase in floodplain proportion of forest and woodland, but also experienced an increase in relative basal area of *Tamarix* (vs. *Populus-Salix*) on the floodplain. Thus, at the wettest restoration sites with improved hydrology we found mixed results regarding shifts in woody vegetation.

- More broadly, we tested the idea that riparian vegetation can re-establish at sites historically degraded by groundwater pumping and stream dewatering, following hydrologic improvement, without need for restoration plantings. We found that following hydrologic restoration streamside wetland communities can recover quickly without any active restoration activities such as seeding or planting. We also found that shifts in woody vegetation can occur within five years following hydrologic restoration at some sites, but that these shifts occur more slowly and are mediated by a more complex set of conditions including climate, geology, and geomorphology.

In addition to answering our initial research questions, we gained new insights into the dynamics and restoration potential of arid riparian systems.

- Over the five years of this study, we found that at some restoration sites hydrology did not improve sufficiently to produce shifts in riparian vegetation. At the driest sites (all three restoration sites at H&E Farm), hypotheses related to the effects of increased surface flow permanence could not be evaluated. Though groundwater levels improved, summer dry season surface flow was never documented at these sites. Hydrologic change is the driver and prerequisite for ecological change in de-watered arid riparian systems. Thus, future work should include hypotheses related to factors influencing the rate and magnitude of hydrologic improvement at particular restoration sites.

- Shifts in woody floodplain vegetation may occur slowly, and large changes should not be expected within any given five year study period. We found subtle changes in woody riparian vegetation at restoration sites over five years (2003 to 2007/2008), which were especially significant when compared to trends at reference sites. However, long term monitoring is recommended in order to continue to document and compare the trajectories at all study sites.

- We observed consistent changes in woody floodplain vegetation at reference sites for the period 2000/2001 to 2007/2008. These sites generally experienced declines in floodplain proportion of forest and woodland and increases in importance of *Tamarix* during this time period. Such changes were likely caused by regional drought and a lack of recruitment opportunities for native pioneer trees.

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VIII. Summary of coordination with CWA

As part of this research project, we initiated a collaborative relationship with the Community Watershed Alliance of the Middle San Pedro Valley (CWA). In 2007 we worked with CWA to establish three study sites near Benson, Arizona. All sites are on private property, and site access was arranged through CWA. We have collected streamside herbaceous data and documented surface flow permanence annually at these sites since 2007, accompanied by a member of CWA. We have maintained communication with landowners, and provided species lists for each site following the 2007 field season. In 2008 we collected woody floodplain vegetation data at these sites, and surveyed channel cross sections at two of the sites. This is an ongoing partnership.

Table 10. Woody vegetation site summary metrics for CWA sites.

	Site metrics (total)		
	Density (stems/ha)	Basal area (m^2/ha)	Vegetation volume (m^3/ha)
CWA1	3012	19	11746
CWA2	3837	13	11985
CWA3	4854	16	7476

Table 11. Relative abundance and importance of woody pioneer species at CWA sites.

	Relative basal area		Relative vegetation volume		Importance value	
	Populus-Salix	*Tamarix*	*Populus-Salix*	*Tamarix*	*Populus-Salix*	*Tamarix*
CWA1	0.04	0.96	0.14	0.86	0.09	0.91
CWA2	0.14	0.86	0.27	0.73	0.21	0.79
CWA3	0.41	0.59	0.34	0.66	0.37	0.63

Importance values calculated as IV = (relative basal area + relative vegetation volume)/2.

IX. Appendix A: Responses to AWPF questions

Below are responses (*italics*) to a set of questions posed by Evelyn Erlandsen, Project Manager, Arizona Water Protection Fund in reply to the original draft of this Final Report.

I. Data Collection and Analysis:

1. When you submitted your application for the research project, you indicated a research paper by Palmer et al. 2005, recommended that data collection "before" restoration can potentially provide valuable information about basic ecosystem characteristics and fuctions, as well as about the efficiency and effectiveness of restoration strategies. In your final report on page 32, you indicated you have no pre-restoration data due to lack of site access prior to restoration. I'm assuming that you are referring to vegetation data collection. Were you able to locate or access pre-restoration data for either groundwater depth information, or streamflow information (USGS), ppt data, or other? Please explain any attempts to obtain pre-restoration data, and how not having it may or may not impact the validity of testing your hypothesis.

This pre-restoration hydrologic data would especially support any assumptions regarding the capacity of the H&E restoration sites to recover, which is discussed on page 33, under Barriers to restoration success. Please offer any comments.

Ideally, pre-restoration baseline data would be available for all restoration sites. However, in reality such data often are not collected or are not available to researchers and managers. For our lower San Pedro River study sites, there is little pre-restoration groundwater depth or streamflow data available. The information that we have is anecdotal, patchy, or consists of estimates made from remotely sensed images. For example, TNC has unpublished data from a few well measurements that indicate a ~2.5 m rise in groundwater levels at H&E Farm after irrigation cessation (see page 7 of this report). In general, groundwater depth measurements are not available for the study sites prior to their purchase by TNC. Similarly, field-collected streamflow monitoring data are not available for the study sites prior to their purchase by TNC. We have tried to discern the likely historic streamflow conditions from anecdotal reports and from historic air photos.

Although I would argue that field-collected site level data are preferable for reconstructing historic conditions at specific local restoration sites, I agree that using surrogate data such as regional climate data or off-site stream gauge data could also be helpful in this regard. Regional precipitation data are available for several sites in the San Pedro River basin and records do generally extend for several decades (e.g., see Western Regional Climate Center, http://www.wrcc.dri.edu/summary/climsmaz.html). Similarly, USGS streamflow records for the gauge at Redington, AZ are also available (see Figure 2 of this report). However, the relationships between this kind of regional data and site level hydrology are difficult to quantify, especially considering the large degree of uncertainty regarding past groundwater pumping rates at the sites. That is, we could model the current relationships between *precipitation/Redington streamflow and site level hydrologic conditions, but such models would not necessarily be applicable to the past due to considerable changes in the water management context. There are currently efforts underway to create realistic, accurate groundwater models for the lower San Pedro River basin (e.g., Whittier and Maddock 2006, Adkins 2009) and such models could be used to reconstruct past hydrologic conditions at our study sites. Such modeling, however, is beyond the scope of the present study.*

2. Table 3, page 15. My understanding is that although both restoration sites are now non-perennial, it is believed that the Three Links Farm restoration sites were historically perennial and that the H&E Farm restoration sites are believed to have been historically, non-perennial. If H&E Farm restoration sites are thought to be historically non-perennial, wouldn't we expect to see "recovery" as successful, if the vegetation data set was to approach a "target" represented by the non-perennial reference site data set? Please explain.

This is certainly a valid perspective, based on the idea that the goal of ecological restoration is to achieve historic conditions. In this view, 'recovery' to conditions typical of non-perennial reference sites might be the desired outcome (assuming these sites represent historic conditions at H&E Farm). However, the stated restoration goals of TNC were to improve riparian conditions through hydrologic enhancement, and specifically to increase the duration and extent of perennial flow. Thus, their goals were not stated in terms of returning to a previous condition. Rather, they wanted to create wetter conditions in the river and riparian zone. In light of this, I think it is appropriate to use the perennial reference sites to define target conditions for the overall restoration project, since these are the wettest sites.

3. Additionally, were there any USGS gages upstream of the Three Links Farm that could have provided data to further our understanding of the flow regime of both restoration sites?

Yes, there are upstream USGS streamflow gauges. However, I would be hesitant to use the streamflow records from these gauges to determine specific flow conditions at the restoration sites. The San Pedro River is spatially intermittent, meaning that flow conditions change along the length of the river due to tributary inputs, channel infiltration, evapotranspiration, groundwater extraction, etc. Therefore, caution must be used when trying to infer flow conditions at a study site from a gauge that is a considerable distance away. Further, the upstream gauges are all within the Upper San Pedro River Basin, which is generally considered to be somewhat distinct hydrologically from the lower basin.

4. Table 3, page 15. I understand you are "summarizing" the data, however, it would be helpful to see the "baseline" data separate from the 2007 and 2008 data so that "trends" can possibly be identified. For instance, on page 30, you refer to the loss of hydric perennials as an indicator of a shift to non-perennial flows. It would be helpful to see the trends for each restoration site within the Farm units, to see if they are moving toward recovery or away from recovery. Please explain.

I have added a table (new Table 4) showing temporal trends in relative cover of plant groups at each farm, and for the two reference site groups. Since we do not have actual pre-restoration baseline data, the first year of data reported is 2003. Also – Figures 6 and 7 should be helpful in determining the existence of temporal trends.

5. The data collection conducted in cooperation with the Community Watershed Alliance (CWA), is included at the end of this report. These sites are outside of the project area and represent "reference" conditions. Please explain why this data set was not included in analyses for this study? Does the information collected support your hypothesis?

We are very pleased to be working with the Community Watershed Alliance to collect riparian data in the Benson area. This is an important area on the San Pedro River, and the sites are critical to our developing understanding of spatial and temporal patterns on the river as a whole. The CWA sites were not included in the analysis of the streamside herbaceous vegetation because we have only collected data at these sites since 2007 and one of the strengths of the present analysis is that it employs long term data. Similarly, since we only have one year of woody data for these sites we cannot assess changes over time in woody floodplain condition. It would be a good idea to re-sample woody floodplain vegetation at these sites in 2013 (5 years after baseline data collection), and to then examine temporal changes. We are continuing to collect herbaceous data annually at the sites, and consider this work to be a priority in our monitoring.

I have examined the CWA site data, and can make some general comments regarding vegetation conditions at the sites. Streamside vegetation characteristics at the CWA sites were generally similar to conditions at other perennial sites – e.g., relatively high total cover, high 1-m^2 species richness, and high cover of wetland plants. The composition of the herbaceous vegetation was also very similar to that of the perennial reference sites. Thus, short term riparian indicators were consistent with our overall results. Woody floodplain vegetation at the three CWA sites appeared to be within the range of variability of our reference sites for 2007/2008. Total woody basal area ranged from 13-19 m^2/ha at the CWA sites, and 9-34 m^2/ha at the reference sites. Tamarix *comprised 59-96% of the total woody basal area at the CWA sites, compared to 14-100% at the reference sites in 2007/2008.*

6. Table 3, page 15. The TNCP perennial reference sites experienced a wildfire during the study period, as you indicated on page 35. Would your use of the CWA data as reference perennial sites aided in the analysis to determine if the restoration sites are approaching "target" conditions?

I consider it appropriate to use the TNCP streamside herbaceous data in the determination of "target" conditions because (1) the vegetation zone immediately adjacent to the river did not burn in the 2005 fire, (2) herbaceous vegetation responds and recovers quickly following environmental changes or perturbations, and (3) hydrology is the prime influence on streamside herbaceous vegetation characteristics on the San Pedro River. Yes, we could explore including the CWA site data in our description of "target" conditions for streamside herbaceous *vegetation. However, there are some reasons to be cautious in this regard: First, the three CWA sites are not technically within the 'Lower' San Pedro River Basin, and thus likely differ a bit in terms of factors such as hydrology, climate, and/or the available species pool. Second, as mentioned above we do not have long-term data for these sites. For these reasons, I did not include the CWA sites in the description of "target" conditions for our lower basin sites.*

7. Figure 8, as you noted on page 33 represents the shift of the vegetation communities towards "target" conditions represented by perennial reference sites. What other data collection or analysis would help us to understand if each of these restoration sites are approaching the thresholds necessary to "drive" tamarisk to cottonwood/willow communities as mentioned on page 2. Thresholds for the San Pedro system were identified as: a. surface flow permanence >76% b. groundwater depth <2.6 m and c. annual groundwater fluctuation <.46m.

We are fortunate that TNC monitors groundwater levels quarterly at H&E Farm and Three Links Farm, monitors instream flow at Three Links Farm, and is willing to provide that data to researchers for scientific analysis. This monitoring requires a substantial commitment of time and resources, but provides critical data for assessing changes in hydrologic conditions at the sites over time. If additional resources were available, I would suggest increasing the monitoring program at the restoration sites and also adding additional monitoring at reference sites. Specifically, I would recommend monthly monitoring of surface flow presence/absence at monitoring stations, and installation of streamside piezometers to document water depth below the channel at each site. Such piezometers are short-lived, as they tend to be lost during floods, but they do provide important information about groundwater depth will they are in place.

8. Figures 14 and 15: page 23 and 24, 3L2, and HE2, tamarisk increased in "patch type proportions".

Yes, the proportion of the floodplain occupied by Tamarix *patches increased at some sites during the study period. As you mention below, this was accompanied by an increase in relative basal area of* Tamarix *at many of our sites. Interestingly, the Importance Value of* Tamarix *increased at 5 out of the 6 reference sites during the study period (see Table 8).*

9. Table 5, page 28: for each site that experienced a decrease in Populus-Salix, there was a correlated increase of Tamarix, and vice-versa (between the baseline data and the 2007/2008 data).

This is due to the method of calculating relative basal area – the metric is the amount of either Populus-Salix *or* Tamarix *basal area as a proportion of* Populus-Salix + Tamarix *basal area. So, if one decreases then the other increases, by definition.*

10. Table 5, page 28: The 3L2 site is the only restoration site that appears to have had a decrease in relative basal area and vegetation volume of Populus-Salix, and an increase in Tamarix, this is also the site that I understand received the most surface flow and represents

restoration that is approaching "target conditions" represented in Table 3 as you have stated in the report.

Site 3L2 was the wettest of the restoration sites during the study period, as evidenced by the hydrologic monitoring data and analysis of the streamside vegetation metrics. While 3L2 experienced an increase in relative basal area of Tamarix*, it also experienced a large decrease in* Tamarix *relative vegetation volume. When these values were averaged together, the Importance Value of* Tamarix *actually increased at 3L2 (a pattern also observed at most of the reference sites). These complexities and differences highlight the merit of monitoring both short-term and long-term riparian indicators in this kind of a study, and also the importance of monitoring both the hypothesized 'drivers' of change (i.e., hydrologic conditions) as well as a suite of 'response' variables. While site 3L2 may have recovered hydrologically, the data support the idea that there is a lag effect in woody vegetation response to improved hydrologic conditions. While total woody basal area has increased at 3L2, the proportion of* Populus-Salix *is still fairly low.*

Recruitment events are required in order for Populus-Salix *to increase on the floodplain. Recruitment of* Populus-Salix *is associated with fall, winter and early spring floods (Stromberg 1998). These floods clear competing vegetation, and/or deposit fresh sediments, to create bare moist patches where seedlings can establish. Seedling establishment occurs in the spring, when moisture is abundant and seeds are dispersed. Long term survival of seedlings, and recruitment to older age classes, depends on the ensuing hydrologic and climatic conditions. Leenhouts et al. (2006) modeled the occurrence of* Populus-Salix *recruitment events on the Upper San Pedro River and found that 6 such events occurred between 1988 and 2002. However, the actual recruitment rate varied depending on site conditions, with no recruitment modeled for some sites. Thus,* Populus-Salix *recruitment is episodic and depends upon the concurrence of a complex set of conditions involving regional climate, river hydrology, and site characteristics. It appears that no major* Populus-Salix *recruitment events occurred during the study period.*

Regeneration of Populus-Salix *may be limited on the lower San Pedro River floodplain by a lack of available "recruitment space" (Stromberg et al. 2010). Although extensive areas of pioneer forest became established on the floodplain in the last century, the area available for ongoing recruitment has become restricted as this space has been occupied.* Populus-Salix *seedling establishment now appears to be occurring in narrow bands along the channel margin (Stromberg et al. 2010, G. Katz unpublished data). Under this current geomorphic scenario, large pulses of* Populus-Salix *recruitment may not occur until extreme flood events create new recruitment surfaces. Floodplain forest establishment following extreme floods is a common, albeit temporally infrequent, style of forest regeneration on free-flowing arid region rivers (e.g., Katz et al. 2005).*

Regarding #8, 9, and 10 above. Why do you think we're seeing this increase in Tamarix at the wettest restoration sites? What observations can you provide that would help recommend any future management strategies to help drive the trend toward more "native" species?

This restoration project was conducted during a period of regional drought, and that climate context has surely influenced our results. As mentioned above, 5 of our 6 reference sites experienced increased Tamarix *Importance Value (IV) during the study period. However, all of these reference sites also experienced an overall reduction in total woody basal area across the floodplain. Thus, though* Tamarix *has increased in relative importance at the reference sites, it has generally not increased in abundance in absolute terms. I hypothesize that Tamarix survival has been higher than* Populus-Salix *survival during this dry period. Both species have declined in absolute terms, but effects have been more severe for* Populus-Salix *which are less drought tolerant species, and appear to have more restricted recruitment windows, than* Tamarix*.*

From a management perspective, it is important to (1) emphasize the role of site hydrology in determining riparian vegetation characteristics, (2) acknowledge the spatial variability inherent in the San Pedro River system, and (2) recognize that a long term commitment is required, in order to take advantage of temporal variability in physical and biological conditions. If the management goal is to increase native floodplain pioneer tree species, then management efforts should prioritize attainment or maintenance of hydrologic conditions that support recruitment and survival of these species. The required hydrologic conditions are not static, but involve dynamic processes (e.g., flooding, drought, sediment movement) that vary in time and space. Site hydrology reflects local and regional physical conditions, and is also affected by management actions at multiple scales. Site level management should therefore be conducted within a broader framework that ideally includes collaboration with managers and stakeholders elsewhere in the basin and the region.

II. Report:
a. Format/content:

1. I was not able to locate all literature referenced, please double-check and revise Section VI, Literature Cited, as appropriate.

Checked and revised as requested.

2. You mentioned site access was not available on some of the sites. Were there any other changes in methodology, procedures, or data collection, or analysis that was originally planned for this research project (and represented in your PLAN)? If so, please note any changes in the revised report.

This was the only substantive change.

b. Lessons Learned:

3. What would you recommend for future research to support your hypothesis? What other data collection and/or analyses would you recommend that would improve our understanding of the hydrologic system and how the restoration sites are or are not responding in a way that supports native vegetation?

We recommend continuation of research addressing the effects of hydrologic restoration on the lower San Pedro River. In particular, ongoing monitoring and analysis to document trends in hydrology, streamside vegetation and woody floodplain vegetation is needed at restoration and reference sites. For hydrology and streamside plant communities, it is imperative that field data are collected at fairly frequent intervals. For woody floodplain vegetation, we suggest exploring the effectiveness of utilizing remote sensing imagery for vegetation assessment (e.g., Stromberg et al. 2010) and collecting of a reduced set of field variables.

This bio-hydrology research would be strongly complemented by further hydro-geologic studies of the groundwater system of the lower San Pedro River. Although understanding of the hydrologic system of the lower San Pedro River basin is improving, a more detailed description of the groundwater conditions, flow rates, and vertical, latitudinal and lateral relationships would greatly inform our understanding of biotic patterns and temporal trajectories. This understanding would enable better predictions regarding restoration outcomes at specific sites.

4. In your original application, you mention that "lag times" and "rates of recovery" are likely to be different for each restoration site. Based on your data collection and analysis what have we learned about this? How often do you think data collection should occur to further our understanding of the hydrology and recovery of this system and why? And how long of a period of time should collection occur? Please explain.

We found that the pace of recovery was different at the two farms where the restoration project was conducted. At Three Links Farm hydrologic recovery was rapid, and streamside wetland communities responded quickly to improved hydrologic conditions. At H&E Farm hydrologic recovery did not progress to levels required to support surface flow presence during the study period and streamside wetland plant communities did not recover. Thus, the differences in streamside vegetation response were due to differences in the rate and magnitude of hydrologic improvement, which is the driving variable for biotic change in this system.

We suggest that data collection should continue at these sites in order to document changes over time. For hydrology, the driving variable, we recommend ongoing quarterly monitoring of groundwater levels and surface flow presence at all study sites. For short term vegetation indicators (streamside vegetation), we suggest annual or bi-annual sampling following the methods used in this study. For long term vegetation indicators (woody floodplain vegetation), we suggest another data collection effort in 2013 (ten years after initiation of the restoration project). Thereafter, woody data should be collected every decade. Such data collection should occur as long as there is an interest in conservation and management of the lower San Pedro River.

5. Would you have done anything differently? Methodology, data collection, hypothesis?

Our methods were effective in allowing us to answer our main research questions. These methods included collection of a robust set of field data, which is somewhat difficult and time *consuming to obtain. In the future we plan to examine the cost-benefits of reducing the number of field collected variables, especially pertaining to woody floodplain vegetation, in order to expedite field sampling.*

6. Briefly evaluate your success in meeting project objectives.

As stated in the Introduction to this report, the overall goal of this project was to assess the effectiveness of a hydrologic-based approach to riparian ecosystem restoration on the lower San Pedro River. To do this the study had four specific objectives -- (1) Document trends in controlling variables, (2) Document short-term indicators of riparian ecosystem change, (3) Document long-term indicators of riparian ecosystem change, and (4) Assess patterns of change and vegetation-hydrology relationships. We successfully accomplished all four of these specific objectives, as described in this report.

7. Does the outcome support your hypothesis? If not, what would you recommend for next steps? How can we effectively measure when a system's riparian degradation is being reversed, or recovered?

Answers to these questions were added to the body of the report in the new section titled, Lessons learned.

8. What is the "take home" message? What "practical" information have we learned that we can share with land managers and inform restoration efforts?

- *Riparian ecosystems are resilient. On the lower San Pedro River, riparian wetland plant communities have the potential to respond quickly to improved physical conditions, without the need for restoration planting or seeding.*

- *Riparian zones are influenced by a variety of processes occurring at multiple spatial and temporal scales. Thus, the success of site scale management can be influenced by regional factors, including drought.*

- *Sites differ in their rates of response to hydrologic restoration measures such as curtailment of groundwater pumping. Geological conditions and reach-scale geomorphic context may affect the rate of groundwater recovery, and should be considered when selecting sites for restoration.*

- *A long term commitment is required. It may take decades or more for hydrologic restoration projects focusing on groundwater recovery to produce discernible results. During this time period, ecosystems will be affected by an array of other environmental factors in addition to the restoration treatment. Thus, project design and management expectations should be addressed at long time scales, and monitoring should occur over decades.*

9. Please include all data, excel sheets, etc, and reference them in your table of contents. The final report is the "comprehensive" report that includes all data.

These are included in a CD to be enclosed with this report.

Additional literature cited in Appendix A (not in main body of report):

Adkins, C. 2009. Solute chemistry and isotope tracers of groundwater recharge, flow paths, and travel times in the Middle San Pedro Basin, Arizona. Master's thesis. University of Arizona.

Leenhouts, JM, JC Stromberg, and RL Scott. 2006. Hydrologic requirements of and consumptive ground-water use by riparian vegetation along the San Pedro River, Arizona: U. S. Geological Survey, Scientific Investigations Report 2005-5163.

Whittier, J. and Maddock, T. 2006. Groundwater flow model of the Lower San Pedro River basin for the sustainability of riparian habitats. Pp. 59-66 in Webb, B. (editor) *Sustainability of water resources and its indicators*. IAHS Publishers.

X. Data CD