A century of riparian forest expansion following extreme disturbance: Spatio-temporal change in *Populus/Salix/Tamarix* forests along the Upper San Pedro River, Arizona, USA

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ARTICLE INFO

ABSTRACT

Populus–Salix forests are a valued riparian vegetation type in western North America. These pioneer, obligate phreatophytes have declined on some rivers, raising conservation concerns and stimulating restoration plantings, but have increased on others. Understanding patterns and causes of forest change is essential for formulating conservation, restoration and management plans. Our goal was to assess spatio-temporal patterns of vegetation change on the Upper San Pedro River in semiarid Arizona, USA, one of the few undammed rivers in the region. Over 100 years ago, intense floods initiated channel incision and substantially altered hydrogeomorphology. Pioneer trees began to establish in the widening post-entrenchment zone as the surfaces began to stabilize. Using a time-series of aerial photographs (1955–2003) we quantified recent change in area of riparian cover types. Analysis indicated that wooded area in the post-entrenchment zone nearly tripled from 1955 to 2003, at the expense of bare ground, and the active channel narrowed appreciably. This forest expansion represents a long-term response to river entrenchment, with the temporal pattern influenced by recent flood cycles and biogeomorphic feedbacks. *Populus–Salix* have established episodically during the infrequent years with high winter flood runoff, sequentially filling available recruitment space. Older cohorts cover wide swaths of the floodplain while young trees form narrow bands lining the channel. Barring extreme flooding, the pioneer forests are expected to senesce over the coming century. An additional factor that has shaped the pattern of post-entrenchment forest expansion is anthropogenic water withdrawal. *Populus–Salix* forest increase has been greatest within a conservation area, where stream flows are largely perennial. In drier, agricultural sectors, *Populus–Salix* have declined while the more deeply-rooted *Tamarix* has increased. Overall, the study reveals that long-term fluctuations in pioneer forest area and age structure are common on dryland rivers, and shows how past events such as extreme floods can interact with recent environmental practices such as freshwater withdrawal to influence riparian forest patterns. This underscores the necessity of a long-term perspective for forest conservation and management.

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1. Introduction

Riparian forests are inherently dynamic. They undergo temporal changes in area, age structure, and composition in response to climate-driven fluctuations in the fluvial processes that regulate population and community processes (Friedman and Lee, 2002; Latterell et al., 2006; Charron et al., 2008). Superimposed on and interacting with these fluctuations are effects arising from human activities. Because there are many ways in which people influence rivers (Patten, 1998; Naiman and Turner, 2000) and many regional variations in riverine hydroclimatology and geomorphology, coverage of woody riparian vegetation has changed in complex ways on rivers throughout the world (Johnson, 1998; Ferreira et al., 2005; Kondolf et al., 2007). On some rivers, the net effect has been increased woody cover (Snyder and Miller, 1992; Friedman et al., 1998; Johnson, 1998; Grant and Murphy, 2005; Beater et al., 2008). On others, forest area has declined (Snyder and Miller, 1991; Snyder and Miller, 1992; Friedman et al., 1998; Johnson, 1998; An et al., 2003).

Within arid to semiarid western North America, *Populus* forests are a valued riparian vegetation type and many efforts have been undertaken to restore riparian lands by planting young trees (Briggs et al., 1994). Contradictory information exists, however, about whether these forests are undergoing regional decline or

increase (Rood and Mahoney, 1990; Webb and Leake, 2006). As is the case for pioneer *Populus* in non-riparian settings (Kashian et al., 2007), there appear to be multiple patterns of change occurring simultaneously within the heterogeneous riparian landscape of western North America (Friedman et al., 1998; Johnson, 1998). *Populus* has declined in the below-dam reaches of rivers where regulated flows no longer meet recruitment needs (Johnson, 1992; Braatne et al., 2007; Nagler et al., 2009; Merritt and Poff, in press). *Populus* forests also have declined where stream diversion or groundwater pumping have caused water tables to drop below root zones (Snyder and Miller, 1991; Rood et al., 1995; Webb and Leake, 2006). In contrast, on some rivers, riparian forests have increased. This can occur as a result of dam-related reduction in peak flows and flood scour (Johnson, 1994; Webb et al., 2001; Shafroth et al., 2002), and also may reflect population-rebound following fuelwood harvest and phreatophyte clearing of past eras (Bahre, 1991; Graf, 1992). Further, some forests appear to have increased at the expense of marshes and grasslands owing to long-term changes in watershed land use and land cover that modified riparian hydrology and soils, fire and flood regimes, and abundance of beaver (Leopold, 1924; Hendrickson and Minckley, 1984).

Flood cycles are paramount in influencing riparian forest patterns (Meyer, 2001; Parsons et al., 2005). Extreme floods can trigger multi-decade sequences of scour and channel widening, typified by establishment of pioneer trees followed by succession to more competitive species (Friedman et al., 1996; Cordes et al., 1997; Katz et al., 2005), creating cycles of *Populus* increase and decline. In dryland regions, precipitation and flood patterns have high temporal variability, and in southwestern USA, rivers underwent particularly extreme flooding in the late 19th and early 20th century following a rapid climatic shift from severe drought to heavy precipitation (Ely et al., 1993). During this same period, the watersheds were affected by intensive land uses including livestock grazing and timber harvest (Bahre, 1991). The combined effect of these climate and land use extremes, for some rivers, was channel entrenchment and subsequent channel widening (Hastings, 1959; Hereford and Betancourt, 2009).

The San Pedro (Arizona, USA) was one such river. Following entrenchment of its channel, floods sequentially eroded the high terrace walls causing the newly developing floodplain/channel complex to widen in subsequent decades. Rates of recruitment of *Populus* and other riparian trees initially were low in the unstable system (Hereford, 1993). As vegetation increased in density, the stream bank and floodplain sediments stabilized and flood intensities decreased, allowing for increased rates of tree recruitment. Ground photos (Webb and Leake, 2006) provide evidence of forest increase during the last century, but satellite imagery provides conflicting information on patterns of more recent riparian vegetation change (Kepner et al., 2000; Jones et al., 2008). The effects of this re-setting of the stream hydrogeomorphology on forest dynamics remain poorly quantified.

Our goal was to determine how past extreme disturbance (flood-induced river entrenchment), subsequent biogeomorphic adjustment processes, and present land and water management practices are interacting to structure riparian forest patterns on a dryland river. We focused on the San Pedro because it is receiving a high degree of conservation attention, with stakeholders using science-driven management to sustain groundwater resources and riparian amenities (Richter et al., 2009). As one of the last undammed rivers in the region, it also serves as a reference site for river restoration. We analyzed a time-series of aerial photographs to (1) assess temporal patterns of change in the hydrogeomorphic zones that support different forest types, (2) assess temporal changes in forest age, composition and abundance and (3) determine how the vegetation trajectories vary over the length

of the river as it traverses land owner boundaries and water withdrawal gradients.

2. Methods

2.1. Study area

The San Pedro River arises in Sonora, Mexico and flows northward to its confluence with the Gila River in south-central Arizona, USA. Our study area extended from the international border (elevation of 1280 m) to the Benson Narrows (1005 m), a river length of approximately 100 km (Fig. 1). The San Pedro Riparian National Conservation Area, managed by the U.S Bureau of Land Management, spans much of the southern study area. The Conservation Area was designated in 1988 at which time off-road vehicle use, sand and gravel mining, livestock grazing and irrigated agriculture were discontinued. The remainder of the study area is predominantly under private ownership.

The study area is semiarid with mean annual temperature of 17 °C and mean annual precipitation of 36 cm at Tombstone (http://www.wrcc.dri.edu/). Stream flow ranges from perennial to intermittent, with conditions drier in the north (Stromberg et al., 2006). The river is not dammed by permanent structures, but surface water is diverted into two canals (St. David Diversion Ditch and Pomerene Canal) in the northern study area. On private land along the river, ground water is pumped from the stream aquifer to irrigate farm fields and pastures. Water also is pumped from the regional aquifer, mainly for urban use.

The geomorphology of the San Pedro River reflects processes operating during and after the late 19th and early 20th century episode of stream incision (Bryan, 1928; Hereford and Betancourt, 2009). The pre-entrenchment surfaces are five or more meters above the active channel and are vegetated mainly by *Prosopis velutina* Woot. woodlands and *Sporobolus wrightii* Munro ex Scribn. grasslands. Irrigated crop and pasture land, and abandoned fields, also are common. We refer to these surfaces as river terraces, although some are occasionally inundated by large floods. The post-entrenchment zone (including the inset floodplain and active channel) is the primary focus of this study. These surfaces range up to 400 m wide and 4 m above the channel and are vegetated by pioneer trees and shrubs (e.g., *Populus fremontii* S. Watson, *Salix gooddingii* C.R. Ball, *Tamarix* sp., *Baccharis salicifolia* [Ruiz and Pav.] Pers.), late-successional woody species (e.g., *P. velutina*) and grasslands. We use the term floodplain in a comprehensive sense to include embedded lower landforms including meander cut-offs and dry secondary channels.

2.2. Aerial photography

Archived aerial photographs were acquired for 1935, 1955, 1978 and 2003 for the entire 100 km study reach (Table 1). The 1935 images were obtained from the Arizona State University Map Library and scanned at 700 dpi. For other images, digital scans were obtained from federal agencies. The scanned photographs were georeferenced in ArcMap using spatially referenced DOQQs (2003) as base maps. From 6 to 50 control points (e.g., road intersections, building corners) were identified per image. Depending on the number of control points, 2nd or 3rd order polynomial transformations were used to convert scanned photographs to approximate rectified orthoimages. The root mean square error was less than 3 m for all but the 1935 photos.

2.3. Hydrogeomorphic zones

The riparian/upland boundary was iteratively delineated using the 1935 and 1955 images based on visual differences in
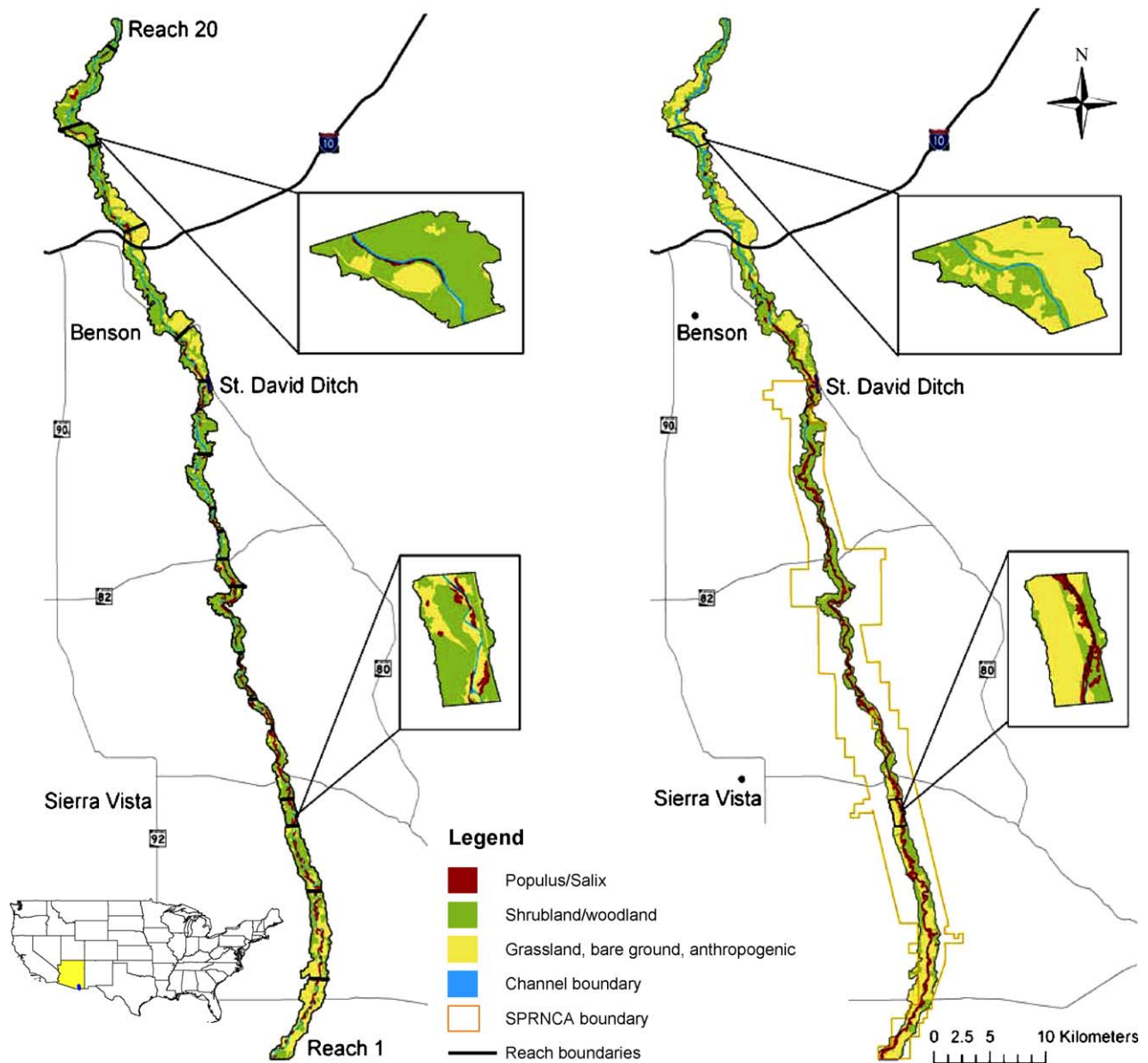
Fig. 1. Cover maps of the Upper San Pedro River riparian zone (U.S./Mexico border to Benson Narrows) for 1955 (left) and 2003 (right). Inset boxes show cover types at a finer resolution. Also indicated are the reach boundaries (shown on 1955 map) and the boundary of the San Pedro Riparian National Conservation Area (shown on 2003 map).

Table 1
Attributes of aerial photographs.

	Source	Scale	Image type	Month flown
1935	Fairchild collection	1:62,500	Black and white	Unknown
1955	U.S. Department of Agriculture	1:20,000	Black and white	January
1978	U.S. Geological Survey	1:25,000	Color	October
2003	U.S. Geological Survey	1:20,000	Color infrared, DOQQs	September

vegetation and in topography (i.e., junctures between flat alluvial surfaces and mountain bases). The 1955 images have greater resolution than those from 1935 but the 1935 images pre-date the conversion of some riparian lands to farm fields allowing observation of pre-development vegetation boundaries. The boundary between the river terraces (pre-entrenchment surfaces) and active floodplain (post-entrenchment surfaces) was delineated using digital elevation maps derived from lidar data (Farid et al., 2006) in combination with USGS quadrangle maps on which the arroyo cut banks had been drawn based on field reconnaissance and aerial photo analysis (provided by Richard Hereford of U.S.

Geological Survey-retired, Flagstaff, Arizona). The terrace/floodplain boundary has shifted through time and was adjusted for individual photo years based on topographic disjunctions visible on the photos (i.e., several meter high breaks between the floodplain and terrace). The terrace/floodplain boundary could not be delineated on the 1935 photos due to low photo resolution. The active channel was delineated as the zone of bare sediments flanking the low-flow channel, and the low-flow channel was identified by presence of a thread of surface water. For intermittent-flow reaches, the most recently visibly scoured channel thread was delineated as the low-flow channel.

Table 2
Cover types mapped within the San Pedro riparian corridor.

Cover type	Description
Populus–Salix forest	Broadleaf forests of *Populus fremontii* and *Salix gooddingii*. Minor occurrences of *Fraxinus velutina* Torr. and *Celtis reticulata* Torr.
Shrubland-woodland	On floodplains, primarily *Tamarix* sp. and *Prosopis velutina*. Also includes smaller shrubs, e.g., *Baccharis* spp., *Hymenoclea sp.* and *Ericameria* sp. On terraces, primarily *P. velutina* with lesser amounts of *Acacia* spp. and smaller shrubs, notably *Atriplex* sp., *Isocoma* sp. and *Ziziphus* sp.
Grassland	On floodplains, grasses including *Cynodon dactylon* (L.) Pers., *Sorghum halepense* (L.) Pers and *Sporobolus* spp., and forbs. Also includes marshlands. On terraces, primarily *Sporobolus* spp.
Bare ground	Bare sediment (floodplain or channel) or unvegetated soil (terrace)
Agriculture	Active and recently abandoned fields
Urban	Buildings, roads, railroads and other infrastructure

2.4. Riparian cover types

As an initial step in determining distinguishable cover types, the 2003 photographs were ground-truthed using field data (Leenhouts et al., 2006 and unpublished data from Gabrielle Katz, Appalachian State University). This process yielded six cover types (Table 2). To standardize the identification process, a decision matrix was developed for each photo series that specified the appearance of each cover type with respect to shape, texture and color. All photographic interpretation was performed by one investigator (M. Tluczek) and inspected by another (A. Hazelton).

To map cover types, polygons were drawn around homogeneous vegetation patches while viewing the images at a scale of 1:3000. A minimum polygon size of 10,000 square meters (1 ha) was used. Some polygons contained mixtures of vegetation types (e.g., forest with herbaceous). Within each polygon, percent cover of each type was visually estimated using cover classes of 0, 1–5%, 6–20%, 21–40%, 41–60%, 61–80% and 81–100%. The area of each type within a stream reach (see below) was calculated by summing the products of the cover class midpoint for each polygon and the polygon's relative area in the reach. The midpoints used in cover calculations were 3%, 15%, 35%, 55%, 75% and 95%; with these midpoint values, the sum of all area-weighted polygon cover values fell within 1% of the measured study area.

Mature *Populus fremontii* and *Salix gooddingii* trees were distinguishable on photographs by their height, broad-leaved foliage, and large canopy. Standing dead *Populus* were also distinguishable and delineated as a subcategory. All other woody vegetation was classified as shrubland-woodland. This category consisted primarily of *P. velutina* and *Tamarix* sp., shrubby trees that are difficult to distinguish from each other on aerial photographs (Nagler et al., 2005). Bare ground included sediments in the active channel and unvegetated areas of the floodplain and terrace. Grassland was delineated from bare ground based on color and texture, but estimates of change in these types have high uncertainty given that annual plants vary seasonally in cover and each photo series was flown in a different month.

2.5. Validation

To assess classification accuracy of the 2003 photos, a 25 m radius was established at each of 60 randomly selected GPS points in the study area. During field visits in 2008, visual estimates of cover of three main structural vegetation types (*Populus–Salix,* shrubland-woodland and non-woody vegetation) were made at each point. These data were compared to the photographic classifications for the polygon within which each GPS point was located. When defining accuracy as having the field cover values fall within the cover class or within one cover class above (for woody vegetation) or within one cover class below (for non-woody vegetation), the accuracy rates are 87% for *Populus–Salix*, 70% for shrubland-woodland and 68% for non-wooded. Main causes of inaccuracy were overestimating woody cover on imagery as compared to field estimates, mis-classifying

young *Salix* in the shrubland/woodland category and mis-classifying dense growth of small shrubs as grassland; the time lag between the photo date and field visits also may have contributed to classification error. Accuracy rates may differ for other photo series because of differences in image type and time of year.

2.6. Temporal and spatial change in cover types

To assess temporal changes, a cover type origin table was generated by first establishing a lattice of 1001 grid points within the study area in ArcMap and classifying each point as to the predominant cover type within its polygon. The predominant cover type for each grid point was tabulated for 2003 as well as for 1955. For the 2003 data set, values were then calculated by cover type for the fraction of points that maintained the same cover type through time and for the fractions that arose from other cover types (as classified in 1955).

To assess longitudinal patterns of change, cover data were calculated by river reach. River reaches had internally homogenous stream geomorphology and hydrology and averaged 5.2 km in length (Stromberg et al., 2006). Total riparian area varies among reaches depending on geomorphology (e.g., geologically constrained vs. unconstrained) and reach length. Also obtained for each reach was the percent of the stream channel that had surface flow during the pre-monsoon dry period using data for 2007 and 2008 compiled by The Arizona Nature Conservancy.

2.7. Tree establishment

In prior studies along the Upper San Pedro River we estimated dates of *Populus* establishment using dendrochronological techniques including tree-coring and excavation and aging of root crown slabs (Stromberg, 1998). The increment cores were collected in winter of 1993–1994 from 112 *P. fremontii* trees distributed among 30 quadrats at 11 locations along the river. These cohort age data were overlaid on recent aerial photographs to provide additional perspective on patterns of riparian forest expansion.

Data also were collected previously on tree diameters of *P. fremontii* and *S. gooddingii* in an additional 31, 100 m² quadrats that spanned the range of size classes present (Stromberg et al., 1996). Stand age for these quadrats was estimated from an age-dbh regression model that predicts tree age from the size of the largest tree in a 100 m² quadrat (age in years = 0.56 dbh in cm, r^2 = 0.82). These data, with prior information collected on topography of the transects, allowed for assessment of distribution of *Populus* cohort age with respect to distance from and above the channel bed.

3. Results

3.1. Hydrogeomorphic surface areas

The active channel, which was wide in the 1930s, decreased substantially in area during the study period (Fig. 2). The low-flow
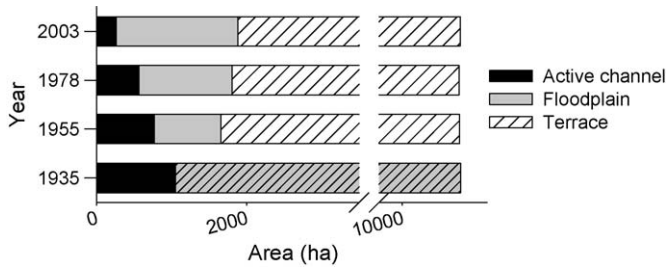
Fig. 2. Change through time in areal extent of hydrogeomorphic zones within the Upper San Pedro riparian corridor. The floodplain and terrace could not be distinguished in the 1935 photos.

Fig. 4. Change through time in area of cover types on post-entrenchment surfaces of the Upper San Pedro River.

stream channel (example shown in Fig. 3) also decreased in area (485 ha in 1935, 423 ha in 1955, 408 ha in 1978, and 203 ha in 2003). The floodplain area, in contrast, increased. Owing to periodic erosion of the terrace walls by large floods, the combined floodplain-channel area (post-entrenchment surfaces) increased by 14% from 1955 to 2003.

3.2. Riparian cover types within the post-entrenchment zone

From 1955 to 2003, the percentage of the post-entrenchment area occupied by woody vegetation increased through time, from 25% in 1955 to 62% in 2003. This was a result both of expansion of *Populus–Salix* forest, which increased nearly three-fold, and of the shrubland-woodland type (predominantly *Tamarix* and *Prosopis*), which approximately doubled in area (Fig. 4). Most of the *Populus–Salix* forests mapped in 2003 arose from land mapped in 1955 as
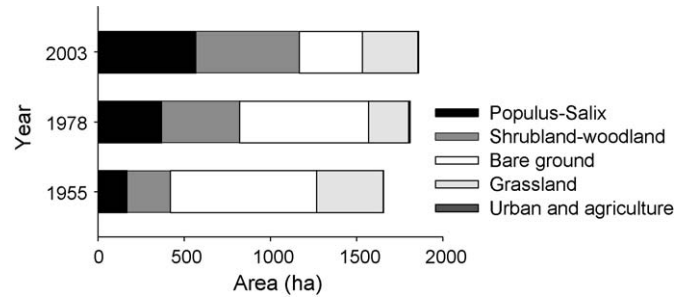
bare ground (inclusive of sediments in the active channel) (Table 3). The shrublands-woodlands arose primarily from preexisting shrubland-woodland, bare ground or grassland. The predominant cover types in the post-entrenchment zone shifted from bare ground (847 ha) and grassland (387 ha) in 1955 to shrubland-woodland (597 ha) and *Populus–Salix* (569 ha) in 2003.

3.3. Tree establishment patterns

Establishment of pioneer trees within the post-entrenchment surfaces has been episodic, occurring during years with suitable winter flood runoff (Fig. 5). This periodicity has created zonation of age cohorts and sequential, but temporally variable, filling of recruitment space. *Populus* cohorts from the 1960s occupy the greatest area, with decreases in cohort band width in subsequent decades (Fig. 6). Although the 1980s and 1990s were decades with
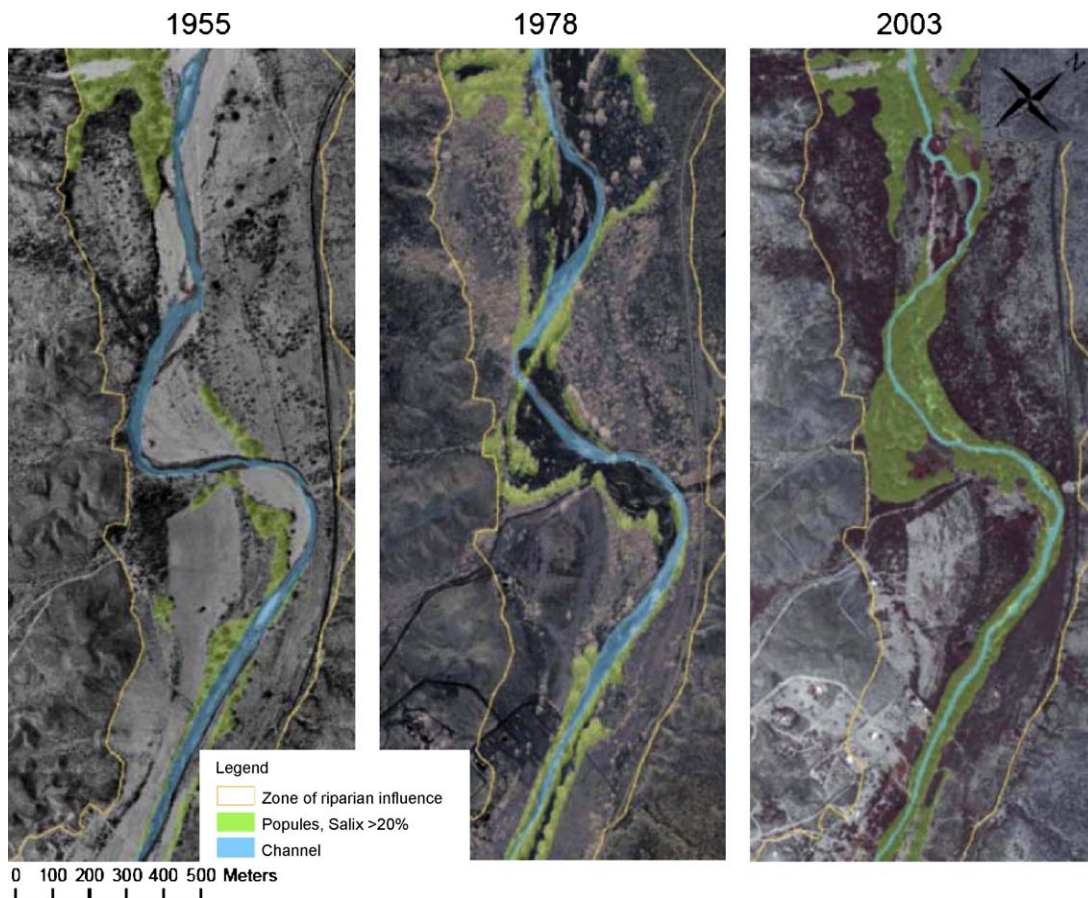

Fig. 3. Representative section of the Upper San Pedro River riparian zone revealing the increase in *Populus–Salix* forests and narrowing of the low-flow channel through time.

Table 3
Cover type origin table. Values indicate the percentage of points mapped in 2003 that arose from cover types as mapped in 1955, for the floodplain/channel zone of the Upper San Pedro River.

	Status in 2003			
	Populus–Salix	Shrubland-woodland	Grassland	Bare ground
Status in 1955				
Populus–Salix	15%	3%	7%	9%
Shrubland-woodland	10%	46%	4%	23%
Grassland	19%	22%	41%	18%
Bare ground	56%	29%	48%	50%
Sum	100%	100%	100%	100%

wet winters the associated winter floods produced only narrow bands of new recruits.

Distance of *Populus–Salix* cohorts from the channel bed increases along the chronosequence, owing to channel migration (Fig. 7). Many of the older trees grow along abandoned channel beds, oxbows and meander cut-offs. The bands of saplings and other young trees form dense, narrow galleries lining the low-flow channel. Aggradation of the floodplain has contributed to the elevational differences that occur along the *Populus–Salix* chronosequence (Fig. 7), based on excavations to root crowns. The slope of the regression line predicting floodplain elevation from *P. fremontii* stand age ($y = 0.025x + 1.3$; $r^2 = 0.29$, $n = 58$ post-entrenchment stands) suggests a net aggradation rate of 2.5 cm per year over the past 90 years. Episodic channel deepening following the initial incision event also has contributed to the elevational differences (Hereford, 1993).
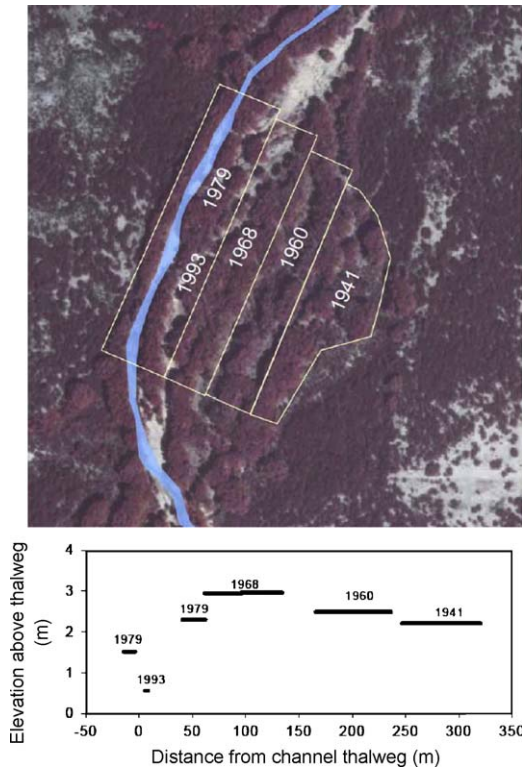

Fig. 6. Top figure: Relative area occupied by *Populus fremontii* cohorts of varying age, for post-entrenchment surfaces within the San Pedro Riparian National Conservation Area. Also shown are decadal averages for the Palmer Drought Severity Index for southern Arizona (middle figure) and for winter (October–March) precipitation at Tombstone, Arizona (bottom figure).

Fig. 5. Representative section of the Upper San Pedro riparian zone indicating zonation of *Populus–Salix* age cohorts. The graph in the lower right indicates location and estimated date of establishment of *Populus* cohorts (via tree-ring analysis) along a riparian transect at Summers site within the San Pedro Riparian National Conservation Area.
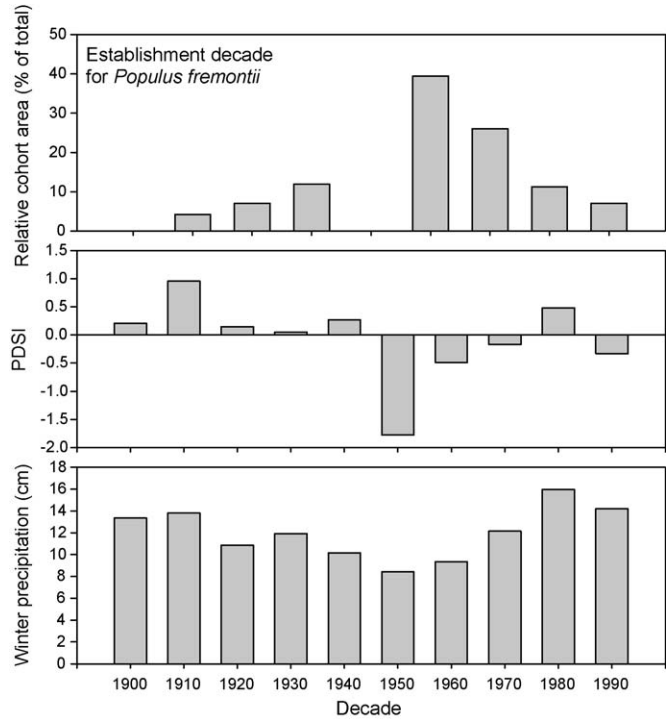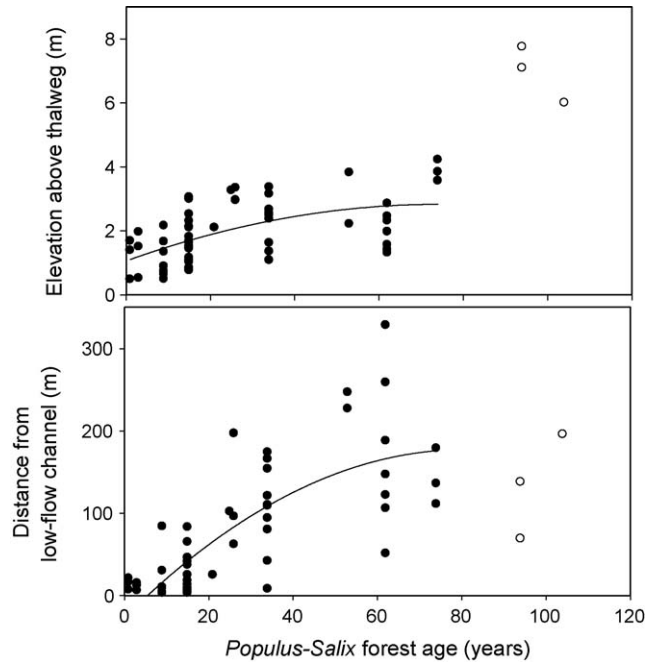

Fig. 7. Distance from and above the San Pedro River low-flow channel for *Populus/Salix* stands of varying age. Each data point represents a forest stand. One-year-old stands established in 1993; the three stands older than 90 years are on pre-entrenchment river terraces. Also shown are quadratic regression lines.

3.4. Riparian cover types within the post-entrenchment zone: spatial patterns

The compositional pattern of forest expansion varied over the length of the river. Of note, *Populus–Salix* forests increased most
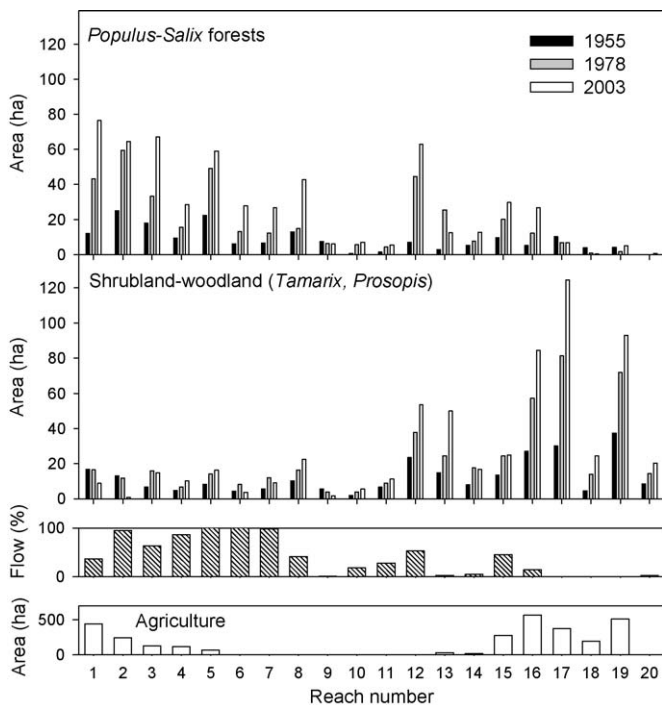
Fig. 8. Top figure: Change through time in area of cover types, by reach, on post-entrenchment surfaces of the Upper San Pedro River. Reach 1 begins at the international border. Reach 14 is the northern, downstream boundary of the San Pedro Riparian National Conservation Area. Also shown is the percent of each reach with perennial stream flow (averaged for 2007 and 2008) and the percent of each reach's river terrace classified as farm land (active or fallow) as of 2003.

extensively in wetter parts of the study area whereas the expansion of shrubland-woodlands (i.e., *Prosopis, Tamarix*) was greatest in the northerly, drier end of the study area (Fig. 8). In two of the driest northern reaches, *Populus–Salix* decreased from 1955 to 2003, countering general trends for this vegetation type. Much of the river in the northern sector has infrequent surface flow, and terraces in this area have many hectares of agricultural fields that are irrigated by diversion ditches or by near-channel wells.

Small pockets (total of 25 ha) of dead *Populus* trees were evident in the 2003 photographs in three reaches (1, 2, and 3, southern end of Conservation Area) although these reaches still showed a net increase in *Populus–Salix*. Riparian forests in these reaches have burned in the past decade and fire is presumed to be the cause of tree death. *Prosopis–Tamarix* declined in area in a total of three reaches from 1955 to 2003 (counter to the prevailing trend), with these declines also attributable to fire.

4. Discussion

4.1. Extreme disturbance and long-term trajectories

Populus, Salix and *Tamarix* all are pioneer trees that require moist bare soil for establishment. Abundance of these species has been influenced by historic river entrenchment of the San Pedro River, an event that set in motion long-term changes in riparian forest dynamics and geomorphic adjustments (Hereford and Betancourt, 2009). In essence, the entrenchment event triggered a long-term pulse of pioneer tree establishment, channel narrowing, and floodplain development. The entrenchment event itself was a proximate effect of extreme floods and extreme climate shifts, and an ultimate effect of land use patterns during the late 1800s and early 1900s that reduced plant cover and destabilized soils.

4.2. Climatic overlay and biogeomorphic feedbacks

One factor has that shaped the temporal process of post-entrenchment forest development is recent flood patterns. As vernally dispersing plants with small, short-lived seeds, seedlings of *Populus fremontii* and *Salix goooddingii* establish during years with sufficient soil disturbance and suitable winter runoff (Shafroth et al., 1998). Seasonal flood patterns undergo decadal-scale shifts along rivers of the U.S. Southwest (linked with changes in Pacific Ocean sea temperatures; Hirschboeck, 2009) and thus suitable recruitment conditions for *Populus/Salix* occur at varying frequency (Stromberg, 1998).

Through time, the cohorts have sequentially filled the available recruitment space during episodic flood events. The forest landscape patterns also have been shaped by biogeomorphic feedbacks between the expanding forests and fluvial processes. As riparian forest area and density increased, channels stabilized, scouring forces decreased, and floodplains aggraded (Hereford, 1993). Collectively, these processes have resulted in decreasing width of potential recruitment zones for young *Populus* and *Salix*. As has occurred on other rivers following extreme disturbance, pioneer tree regeneration is now shifting toward a fringe replacement mode, typified by narrow bands of seedlings along the channel margin (Cordes et al., 1997). Barring extreme future disturbance, a large percentage of the *Populus–Salix* forests along the San Pedro River are expected to senesce without replacement and cede to *Prosopis* forests and riparian grasslands (Dixon et al., 2009).

Increase in pioneer forest area following extreme disturbance is not unique to the San Pedro. Major floods have triggered multi-decade sequences of *Populus* establishment and channel narrowing on various rivers of western North America (Turner, 1974; Friedman et al., 1996; Cordes et al., 1997; Katz et al., 2005). In some cases, as on the San Pedro, the process of pioneer forest expansion and succession to competitive species can occur over centuries (Johnson, 1994). There are, however, some rivers in which the physio-climatic settings produce frequent intense floods, thereby perpetually maintaining the riparian forests in an early successional stage (Campbell and Green, 1968).

4.3. Stream diversion and groundwater pumping

Another process that has influenced post-disturbance forest landscape patterns is freshwater withdrawal. Conversion of riparian land to agricultural land or urban use puts high demands on water resources, and the associated stream diversion and groundwater pumping cause stream flows and water tables to decline (Kingsford, 2000; Fitzhugh and Richter, 2004). On the San Pedro, cultural and physical factors have produced differing water availabilities over the length of the river, and these have created spatial patterns in the composition of the riparian forests. Stream flows and water tables are reduced in the northern sections of the study area, in part because of long-term stream diversion and high rates of groundwater pumping for irrigated agriculture. These drier conditions have favored *Tamarix*, an introduced pioneer shrubby tree that is a deeply-rooted facultative phreatophyte (Glenn and Nagler, 2005). The wetter conditions maintained in the Conservation Area have favored the obligate phreatophytes *Populus* and *Salix*. Temporal shifts or spatial gradients from *Populus–Salix* to *Tamarix* in response to decreases in water availability also have occurred along other rivers in the region (Snyder and Miller, 1991; Stromberg et al., 2007; Akasheh et al., 2008), and parallel the shifts towards more drought-tolerant species that have occurred in other dryland regions following stream flow or groundwater reduction (An et al., 2003).

4.4. Livestock grazing

Another type of agricultural land use common along the San Pedro River, livestock grazing, also has influenced vegetation development. Limited data suggests that livestock grazing can favor survivorship of *Tamarix* over the more palatable *Populus* and *Salix*. Thus, the combination of livestock grazing, water withdrawal and the arrival of *Tamarix* along the river in the 1950s contributed to shifts towards *Tamarix* in some reaches (Stromberg et al., 2007).

We speculate that livestock grazing also has affected riparian vegetation by protracting the processes of post-disturbance forestation. Cattle trample and browse tree seedlings (Auble and Scott, 1998) but also increase recruitment space for pioneer tree seedlings by reducing competitive grass cover. During the first decades following entrenchment, cattle may have reduced tree seedling abundance via trampling and browsing. Although grazing occurred at more moderate levels following reforms of the 1930s, livestock may have continued to destabilize the channel by reducing graminoid cover and creating patches of bare mineral soil.

Following exclusion of cattle from the Conservation Area during the 1980s, riparian vegetation cover increased (Krueper et al., 2003). Jones et al. (2008), using satellite imagery, similarly noted an increase in "greenness" in the Conservation Area but not in the area to the north, with the discrepancy attributed to differences in grazing pressures and/or water availability. Woody pioneers typically undergo a pulse of regeneration following livestock exclusion (Sarr, 2002) but this rate can decline over time as soil-stabilizing graminoids establish. Functionally, this reflects a shift from pioneer species to more competitive species (Green and Kauffman, 1995). In the Conservation Area, the dense graminoids that line the perennial stream channel, in conjunction with woody vegetation, are stabilizing bank sediments, inducing local channel deepening, and reducing formation of open surfaces during channel migration. The net effect is reduced area for establishment of pioneer trees.

4.5. Fire

Fire regime has changed through time along the San Pedro and other desert rivers. Fire suppression, both passive (via grazing-reduced fuel loads) and active, was common in the San Pedro valley in the 20th century, and likely favored survivorship of *Populus* and other woody species as observed in other regions (Grant and Murphy, 2005). More recently, the post-1988 exclusion of livestock from the Conservation Area is resulting in an increase in fuel loads which, combined with increased human presence, is causing frequent fire. These fires locally reduce forest canopy and increase cover of riparian grasses (Stromberg et al., 2009), and perhaps are shifting the vegetation towards a state more reminiscent of the pre-entrenchment condition.

5. Conclusion and management implications

The century-scale biogeomorphic response to the extreme disturbance of river entrenchment that is playing out on the San Pedro River suggests that a long-term perspective is needed for assessing forest conservation needs. Others have noted that long time-frames are needed to assess changes on dammed rivers, where decades may elapse before the pre-dam trees senesce without replacement by new recruits under the post-dam management regime (Katz et al., 2005; Andersen et al., 2007). A long-term perspective is a key component of ecosystem management, but one which is difficult to reconcile with the time scale of human decision making.

An understanding of historic legacies and of mechanisms shaping forest structure can aid river managers in several ways. For example, federal agencies such as the U.S. Bureau of Land Management use various indicators as a guide for determining whether riparian ecosystems are in proper functioning condition (Prichard et al., 1998). One such indicator is the presence of a diverse age mix of pioneer trees. In dewatered or flood-suppressed reaches, low rates of *Populus* recruitment may indeed indicate management failure. Our study, however, suggests that low rates of recruitment also may be an outcome of biogeomorphic responses to past extreme disturbance.

An understanding of the processes that shape forest structure also is important for informing restoration efforts. The San Pedro, as one of the few undammed perennial rivers in the American Southwest, provides an example of target riparian conditions for restoration of degraded rivers. For sites that serve as restoration templates, it is informative to know the degree to which their vegetation is a product of cultural vs. natural influences (Kondolf et al., 2007) and of current environmental conditions vs. historic legacies (Walter and Merritts, 2008). This study, by indicating the great range in forest cover and age class distribution that has occurred through time on the San Pedro River, suggests that multiple ecological states should be considered within the realm of target conditions.

Finally, knowledge of riparian forest trajectories can aid watershed planners in achieving sustainable use of ground water and in projecting future water needs of riparian vegetation (Richter et al., 2009). Water used by riparian vegetation is a large component of basin water budgets in some dryland areas, and data on the changing area of riparian cover types (thus evapotranspiration rates) is critical for calibrating regional groundwater models. In turn, well-calibrated regional groundwater models are an important tool for projecting response of groundwater-dependent vegetation to climate change. In the American Southwest, increasing aridity is expected to reduce stream water tables (Serrat-Capdevila et al., 2007). Use of groundwater models in predicting effects of hydrologic change on riparian vegetation and water budgets will be enhanced by overlying trajectories of forest change.

Acknowledgements

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