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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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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.

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

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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