# Assessing the Impacts of Land Use Change on Water Availability, Management, and Resilience in Arid Region Riparian Corridors: A Case Study of the San Pedro and Rio Sonora Watersheds in Southwestern USA and Northwestern Mexico

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*For presentation at the XIV World Water Congress of the International Water Resources Association*

*Porto de Galinhas, Brazil, September 25-29, 2011*

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**Abstract**

Riparian corridors in arid regions provide vital ecosystem services but are under pressure due to growing competition for scarce water, increased aridity and hydrologic variability under climate change, and ecosystem fragmentation resulting from urban development. We employ a social-ecological systems (SES) framework to examine and assess land use and land cover change in the riparian corridor of two US-Mexico border region rivers: the Upper San Pedro River that crosses from Sonora state to Arizona, and the San Miguel River in Sonora. We utilize remote sensing of satellite imagery and climate information to examine inter-annual (May - October) and intra-annual (May - May; October - October) vegetation change over the 1990-2010 period at spatial scales from the watershed to riparian buffers of 1 km and 5km. Expanding on two potential system conditions at either end of a gradient from primarily natural to predominantly anthropogenic, we consider how the multi-scale vegetation change history can provide insights into the resilience of arid region riparian corridors. Land cover change analysis can directly contribute to resilience theory when linked to an examination of the changing capacity of an SES to provide diverse ecosystem services under shifting conditions, as thresholds are approached or crossed.

**Keywords:** riparian resilience; land use/land cover change; remote sensing

## 1. Introduction

Riparian ecosystems provide a disproportionately wide range of ecosystem services. The Millennium Ecosystem Assessment (MA 2005) defines ecosystem services as the benefits derived from ecological processes and categorizes these services into four groups: provisioning services, regulating services, supporting services, and cultural (nonmaterial benefit) services. The riparian zone has been defined as "the area from the edge of the stream bank to the external visible line of the canopy where an abrupt change in vegetation height, types, and amount occurs" (Johansen and Phinn 2006). In addition to being vital habitat for diverse flora and fauna species, riparian corridors assist in controlling non-point source pollution, help to maintain cool water temperatures through shading, and afford numerous cultural, recreational, and aesthetic values (Bagstad et al. 2005; Ashraf et al. 2010; Wang et al. 2010). In arid and semi-arid regions, the services provided by riparian ecosystems are even more crucial than in more water abundant regions. Riparian vegetation structure provides protection against flooding, by attenuating peak discharge (Forzieri et al. 2010). In ecosystems, such as the Sonora Desert, that experience intense seasonal precipitation due to the North American Monsoon (NAM), the ability of the riparian area to act as a first line of defense in moderating flood damage is important. These areas also play key roles in water infiltration and aquifer recharge, necessary ecosystem services in arid regions with large populations, both human and non-human, that depend on groundwater for survival. However, the quality of riparian ecosystems is threatened due to human interventions such as flow regulation, urban and agricultural activities that alter nutrient and sediment inputs, loss of vegetation species and cover, and the introduction of invasive and exotic species (Ashraf et al. 2010; Fernandes et al. 2011).

Ecological thresholds are defined as the points at which there is an abrupt change in an ecosystem quality, property or phenomenon, or where small changes in an environmental driver overcome the resilience of the system and produce large responses in the ecosystem (Groffman et al. 2009). Ecosystem resilience is "the capacity of a system to absorb disturbance and still retain its basic function and structure" (Walker and Salt 2006, xiii). Once a system crosses a threshold and reorganizes in an alternative system state, the new regime may have system dynamics, properties, and functions that differ markedly from the previous system state. Importantly, the capacity of the social-ecological system (SES) in the new, alternative system state to provide the range of goods and services that sustain well-being is often diminished (though in some instances, may be enhanced). In SES with strong two-way coupling, non-linear responses are characteristic (Werner and McNamara 2007) and are often instigated when thresholds, or transition points, between alternate states are surpassed in either system (Gunderson and Holling 2002; Holling 2001). The system state is the set of properties that define what the system is, what parameters characterize it, and describe the system's content and processes. Human societies respond not only to actual changes that occur in the biophysical environment, but also to perceived and anticipated changes, further complicating the interactions and feedbacks between the coupled systems (Scheffer et al. 2001). These systems change constantly through co-evolution and adaptation (Folke et al. 2002) in order to remain resilient to internal and external disturbances, such as climate change, technological advances, and new government policies. However, even in systems with high inherent resilience, such as riparian ecosystems (White and Stromberg 2011), intensive anthropogenic alterations can cause resilience to decline resulting in the ability of progressively smaller shocks to cause the system to lose its capacity to sustain a certain regime.

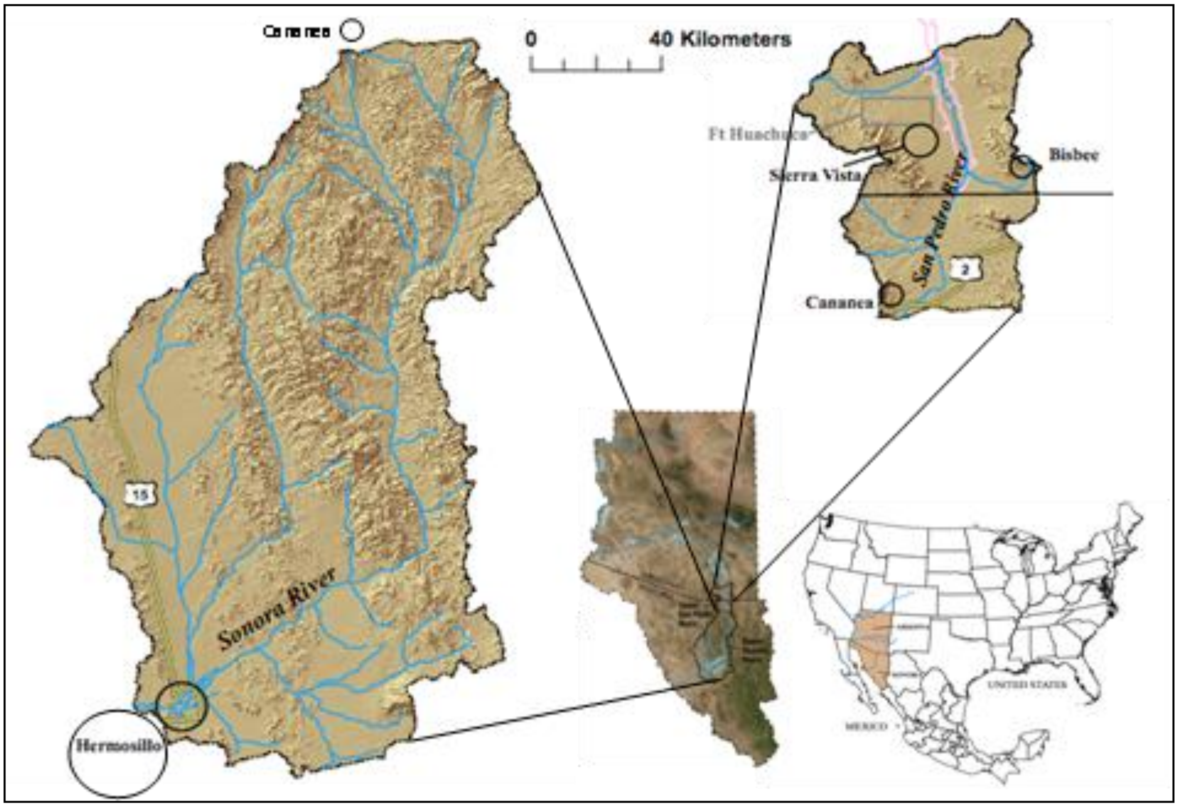


Figure 1: Study area map: Upper San Pedro and Rio Sonora watersheds (note: the Rio San Miguel watershed is a sub-basin of the Rio Sonora watershed)

In arid regions, growing competition for scarce water resources and predictions of increased aridity and modified precipitation seasonality under climate change further stress these sensitive systems. In the US-Mexico border region (Figure 1), riparian ecosystem functions support a wide range of economic activities, including ranching, agriculture, mining, recreation, and tourism. In the riparian corridor, biodiversity is critically dependent on hydrologic processes, specifically surface flow, shallow groundwater, and water quality, which are influenced in complex ways by both direct human intervention and broader climatic and landscape-scale processes. For example, aquifer depletion, due to excessive groundwater pumping to sustain agriculture and urban areas (Scott et al. 2010), reduces the amount and timing of water available to ecological communities in the riparian corridor.

Fernandes et al. (2011) detail the impacts of adjacent land use change on riparian systems. The authors argue that the surface water extraction, groundwater pumping, grazing, nutrient inputs, and replacement of riparian forest with crops often concomitant with agricultural production, can result in a loss of riparian habitat complexity, increased stand mortality and decreased growth rates, and impacts on the ability of species, such as cottonwoods that depend on seasonal flooding, to successfully reproduce. Urban development is responsible for increased runoff and sediment, replacement of riparian habitat with roads and infrastructure, habitat fragmentation, increased levels of point and non-point pollution, and the introduction of exotics (Fernandes et al. 2011). Importantly, the distributions of streamside plants, which comprise the structure vital for providing many ecosystem services, are dependent on numerous factors, including depth to the water table, rooting characteristics, and the riparian substrate geology, all of which are sensitive to the processes of land use change, including proximal agricultural and urban development (Amlin and Rood 2002).

In light of the importance of riparian ecosystems and the abundance of critical functions that they provide it seems obvious that the protection, restoration, and monitoring of these ecosystems would be a paramount concern. However, there is limited understanding of the combined effects of anthropogenic land use change and natural climate variability on the resilience of complex riparian systems in arid regions. Although, efforts to conserve these areas have been become a priority in the United States, Jones et al. (2010) note that little is actually known about whether or not cumulative efforts to restore and protect riparian zones are succeeding in affecting rates of riparian habitat preservation nationwide. Similarly, Goetz (2006) argues that approaches are needed to monitor changes that are taking place in riparian vegetation, to target restoration activities, and to assess the success of previous management activities.

With these gaps in understanding in mind, our research asks: 1) how do the processes of land use and land cover change in arid border watersheds affect vegetation patterns in riparian zones? and 2) how can land cover change information be used to evaluate the system state in relation to a set of potential thresholds? For the purposes of this analysis, thresholds are pre-defined based on postulated SES dynamics. The objectives of this research are twofold: 1) to examine and assess land use and land cover change in the riparian corridor of two US-Mexico border region rivers, the San Pedro River and the Rio San Miguel; and 2) to investigate the potential contribution of vegetation change information to the theoretically imperative, yet empirically difficult, task of determining the position of a riparian system in relation to tipping points, beyond which the functions of the system may change drastically and irreversibly. We begin with a brief review of the conceptualization of thresholds in the resilience literature and the current state of the art of utilizing remote sensing to determine vegetation change in riparian areas. Next, we assess both intra-annual (May to October: 1990, 1994, 1999, 2005, 2010) and inter-annual (May to October: 1990, 1994, 1999, 2005, 2010) vegetation change at multiple spatial scales (watershed scale, 1 kilometer riparian buffer, 5 kilometer riparian buffer) in the two study area watersheds (Figures 2 and 3). We incorporate the results of the vegetation analysis into an investigation of system conditions at either end of a gradient from primarily natural to predominantly anthropogenic. We argue that land cover change analysis can directly contribute to resilience theory when linked to an examination of the changing capacity of a SES to provide a range of ecosystem services under shifting system conditions, as thresholds are approached or crossed.

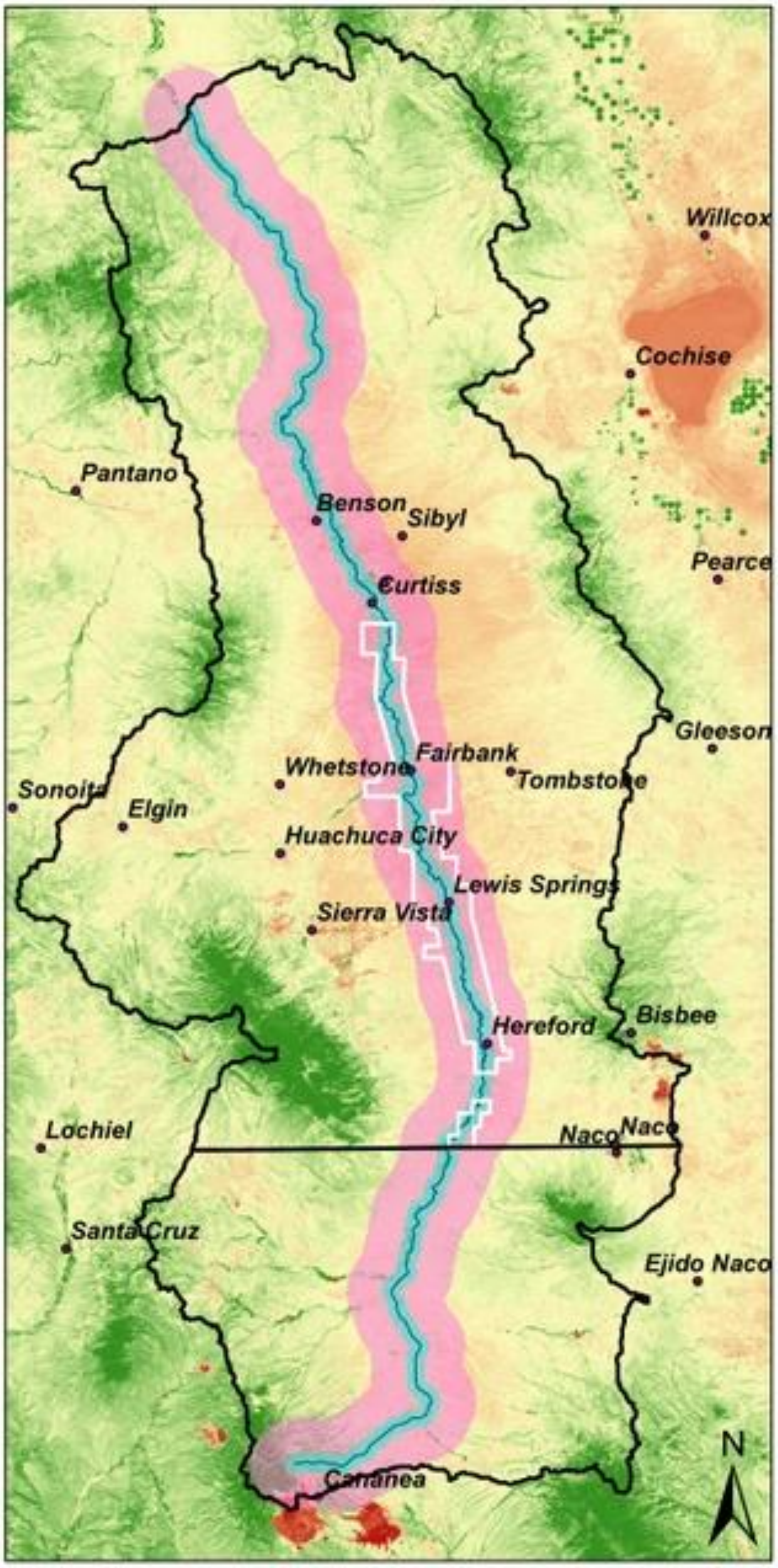

Figure 2: Map of the San Pedro River watershed highlighting the multiple spatial scales of analysis: watershed scale (black outline), SPRNCA (white outline), 1 kilometer riparian buffer (light blue buffer), and 5 kilometer riparian buffer (pink buffer). The background of the map depicts the NDVI for May 11, 2010, with red being areas of low vegetation and green, areas of high vegetation.

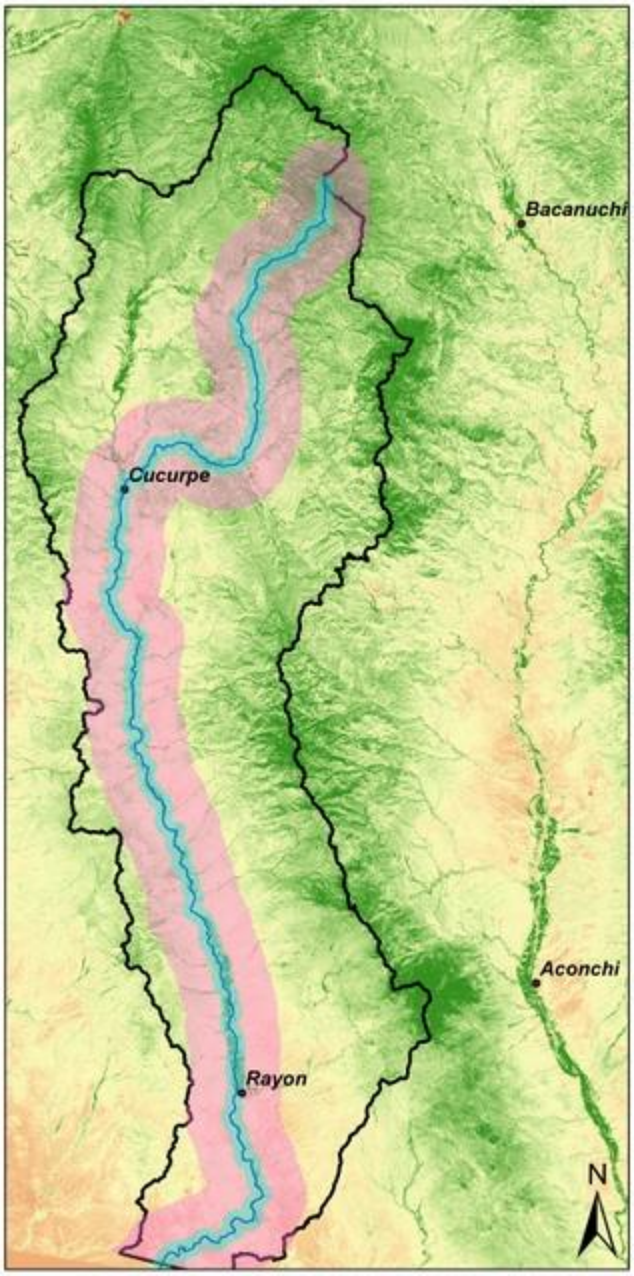

Figure 3: Map of the Rio San Miguel watershed highlighting the multiple spatial scales of analysis: watershed scale (black outline), 1 kilometer riparian buffer (light blue buffer), and 5 kilometer riparian buffer (pink buffer). The background of the map depicts the NDVI for May 11, 2010, with red being areas of low vegetation and green, areas of high vegetation.

## 2. Literature Review

*Resilience and Thresholds in Riparian Systems*

Thresholds are tipping points of social-ecological systems (SES) at which abrupt changes may occur in the function and configuration of the system. Scheffer et al. (2009) define a threshold as "a relatively sharp change from one regime to a contrasting one, where a regime is a dynamic of a state of a system with its characteristic stochastic fluctuations." Processes and structures that mutually reinforce one another, known as positive feedbacks, sustain dynamic and path-dependent stability regimes, altering the equilibrium point of a SES. As conditions change, the system state can shift from one stable point to another, changing the shape of the basin of attraction, such that the position of the system in relation to an existing threshold is altered.

A change in the condition that a system experiences can drive the change in the system state. Where conditions are near a threshold, a small change in conditions can cause a drastic shift in the system state. For example, as a system looses resilience, it takes increasingly smaller disturbances for the system to lose its capacity to sustain a certain regime and instead, to cross the threshold. In fact, it is often through unnoticed changes in slow variables that the system can pass a threshold and reorganize into alternate system state. Although this theoretical perspective assumes that there exist alternative stable states based on the nature of the relationship between conditions and the system state, the ecosystem services provided in an alternate system state may be less desirable and moving back to the previous state may difficult, if even possible, once a threshold is crossed. Informed by the research of Marten Scheffer and other resilience theorists, broadly, and previous research by Juliet Stromberg and colleagues regarding riparian resilience, specifically, we are interested in identifying critical thresholds in the fundamental processes that sustain riparian SES and the potential to detect early-warning signs that a system threshold may soon be reached.

In July 2005, the failure of traditional governance structures to effectively manage groundwater withdrawals in the Upper San Pedro Basin (USPB) in Arizona became exceedingly clear. For the first time on record, the San Pedro River stopped flowing at the Charleston gauge, a condition which persisted for ten days (Saliba and Jacobs 2008). The dewatering of the Upper San Pedro, through intensive groundwater extraction, resulted in a shift to an alternative equilibrium state, from a mesic riparian to a xero-riparian system. Research findings in a nearby riparian system, the Salt River, suggest that altering the fundamental processes that shape vegetation dynamics in riparian SES, specifically resource availability and flood disturbance, is a likely factor in eroding resilience and pushing the system over a tipping point (White and Stromberg 2011).

Ernston et al. (2010, 533), following Carl Folke, conceptualize ecosystem services as emergent from interlinked processes at multiple scales, arguing that “different regimes uphold distinct sets of ecosystem services, and some ecosystem services could be lost (and others emerge) when a new regime is established.” Thus, ecosystem services are themselves not directly controllable (Ernston et al. 2010), instead the underlying processes and mechanisms of assembly associated with the desired state must be identified and restored to result in a self-sustaining resilient system (White and Stromberg 2011) that provides the desired set of ecosystem services.

In addition to eroding resilience through anthropogenic disturbance, human intervention through governance and institutions often seeks, both explicitly and implicitly, to enhance the adaptive capacity of an SES, defined as “the ability of a system to prepare for stresses and changes in advance or adjust and respond to the effects caused by the stresses” (Engle 2011, 647). Ernston et al. (2010) conceive of the role of governance as purposeful collective action among a range of stakeholders with the goal of sustaining and/or improving a current regime, hence purposefully enhancing the system’s adaptive capacity. The authors argue that following resilience theory, human systems should adapt and integrate to promote restoration of ecological processes rather than defend against slow changes by altering the landscape, as historically has been favored through large-scale environmental engineering projects. The human system should be viewed as integrated within the larger, dynamic regional ecosystem, a reconceptualization that allows for regional “habitats” to be examined in terms of the ecosystem services they currently provide, or have the potential to provide, such that interventions could be prioritized to generate a range of ecosystem services at multiple scales (Ernston et al. 2011). The complexity inherent in human institutions and decision-making, which include implicit valuations of ‘desired’ ecosystem services for societal well-being, based on a specific set of services valued by specific groups of people at particular times and places, further complicates the ability to identify critical thresholds in SES (Robards et al. 2011). Young and Levy (1999) define institutions as “systems of rules, decision-making procedures, and programs that give rise to social practices, assign role to the participants in these practices, and guide interactions among the occupants of relevant roles” (14). Conca (2006) contends that the process of role definition in institution building affects behavior, as institutions not only establish the rules of the game, but also the roles of the players, which consequently shape social (and human-environment) relations through processes of identity formation and the generation of expectations and priorities. For example, in relation to ecosystem service provisions, human preferences tend to prioritize provisioning services over regulating services, with both of these prioritized over cultural and supporting services (Robards et al. 2011). In this vein, a potential problematic outcome of human intervention meant to increase adaptive capacity is maladaptation, whereby an action taken to reduce or avoid vulnerability instead serves to increase vulnerability, at different temporal or spatial scales (ie. long term vs. short term vulnerability). Barnett and O’Neill (2010) outline five maladaptation pathways, describing that interventions may inadvertently, 1) increase emissions of greenhouse gases, 2) disproportionately burden the most vulnerable, 3) have high opportunity costs, 4) reduce incentives to adapt, and 5) set paths that limit the choices available to future generations.

*Remote Sensing of Riparian Systems*

Satellite remote sensing is an important tool for monitoring riparian vegetation. Moderate and high resolution satellite and aerial imagery has been used in a number of applications with regard to assessing vegetation presence, structure, biomass, and land cover change in riparian corridors. Accurate and cost effective mapping of riparian environments is important for assessing riparian zone functions associated with water quality, biodiversity, and wildlife habitat (Johansen et al. 2010). The large land area covered by remotely sensed imagery has been found to be more cost-effective than field assessments for large regional studies (Fernandes et al. 2011).

However, due to the unique features of riparian ecosystems, namely the limited width of the riparian zone and the spatial and temporal heterogeneity of biological and physical processes, previous research has found that high and very high spatial resolution (< 3 meters) is necessary for most remote sensing applications (Harms and Grimm 2008; Ashraf et al. 2010; Forzieri et al. 2010; Johansen et al. 2010). For example, Forzieri et al. (2010) produced the most accurate supervised classification of riparian vegetation using a method that fused Quickbird satellite imagery (2.4 meter spatial resolution) and Light Detection and Ranging (LiDAR) data. Ashraf et al. (2010) conclude that spatial resolution is the most significant factor influencing the accuracy of freshwater vegetation classification in New Zealand, but recognize that time and cost are both important trade-offs to be considered. Although Johansen et al. (2010) argue that SPOT data (10 meter spatial resolution) is too coarse to assess structural riparian ecosystem metrics, Goetz (2006) notes that moderately high spatial resolution data, such as Landsat (30 meter spatial resolution), can be used to successfully determine the area of land cover of classes, such as urban, forest, and agriculture, and to assess changes in the overall presence and absence of vegetation. These spectral properties can then be correlated to biophysical indicators to model processes such as sedimentation, nutrient cycling, and water quality.

Vegetation indices are "dimensionless, radiometric measures that indicate relative abundance and activity of green vegetation, including leaf area index, percentage green cover, chlorophyll content, green biomass, and absorbed photosynthetically active radiation" (Jensen 2005, 310). Vegetation indices are designed to maximize sensitivity to plant biophysical parameters, normalize external effects, such as sun and view angle and atmospheric differences, and normalize internal effects, such as topography and soil backgrounds (Jensen, 2005).

The Normalized Difference Vegetation Index (NDVI) was developed by Rouse et al. (1974) and is calculated as:

$$\mathrm{NDVI} = (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red}),$$

where ρ indicates reflectance and the red band is the portion of the electromagnetic spectrum between 600 and 700 nanometers (nm) while the near infrared (NIR) is the spectral band between 720 and 1300 nanometers. Jensen (2005) states the advantages of NDVI as the ability to monitor seasonal and interannual changes in vegetation growth and that the process of ratioing reduces many forms of noise that present in multiple bands of multiple-date imagery. However, limitations of NDVI are its sensitivity to canopy background variations, saturation of the signal in high-biomass conditions, and that the index is non-linear and can be sensitive to noise from atmospheric path radiance (Jensen 2005).

## 3. Study Area

*Upper San Pedro River*

The San Pedro River, a transnational body of water, originates in northern Sonora, Mexico and flows north into the United States through Arizona where it meets the Gila River, which eventually flows into the Colorado River (Browning-Aiken et al. 2003). The San Pedro River is a 1,875 square mile basin that encompasses diverse and ecologically sensitive ecosystems, including the San Pedro Riparian National Conservation Area (SPRNCA), varied topography, and an eclectic mix of populations, ranging from the urban center of Sierra Vista to the military base, Fort Huachuca, to the rural cotton farmers and cattle ranchers of the rapidly shrinking agricultural lands (Browning-Aiken et al. 2007).

The combination of highly variable precipitation patterns, heavily irrigated agriculture, rapid population growth, and the junior status of San Pedro River permit holders to Colorado River water from the Central Arizona Project, has resulted in steadily increasing groundwater withdrawals that currently exceed the natural rate of recharge (Browning-Aiken et al. 2003; Kepner et al. 2004). Within the United States portion of the basin groundwater pumping has caused the San Pedro River to lose over half of its historical perennial surface water flow, a condition aggravated by high well densities in close proximity to the river (Browning-Aiken et al. 2007).

Principal recharge of the alluvial aquifer, which holds much of the available groundwater in the upper basin, depends on streambed infiltration and mountain front recharge (Pool and Dickinson 2006). The USPB receives between 300 to 750 millimeters of precipitation per year, with 65% of precipitation occurring between July and September during the monsoon season (Browning-Aiken et al. 2007). The timing of the majority of precipitation during the summer season exacerbates water scarcity in the basin. The high rates of summertime potential evapotranspiration (PET), estimated at ten times the amount of annual rainfall in the lower elevations, reduce the amount of water available to naturally recharge the aquifer (Pool and Dickinson 2006). Recharge in the basin is also sensitive to El Niño Southern Oscillation (ENSO), which causes high interannual variability in winter precipitation.

To overcome the environmental degradation occurring to the San Pedro River riparian corridor due to groundwater exploitation and urban development, in 1988, the US Congress federally designated a 40-mile conservation area, known as the SPRNCA. The purpose of the designation was to protect and enhance 56,000 acres of key desert riparian ecosystem, which is home to 84 mammal species, 14 fish species, 41 reptile and amphibian species and 100 bird species. The San Pedro River is also a critical flyway for North-South migration of birds, and the SPRNCA provided habitat to over 250 migratory bird species, making it one of the top ten birding destinations in the world. However, a number of factors, both negative and positive have impacted the success of the SPRNCA, including steady population growth in the city of Sierra Vista, intensive groundwater withdrawal (Figure 4), decreasing precipitation (Figure 5), and the removal of grazing and most of the irrigated agriculture from the riparian area (Figure 6).

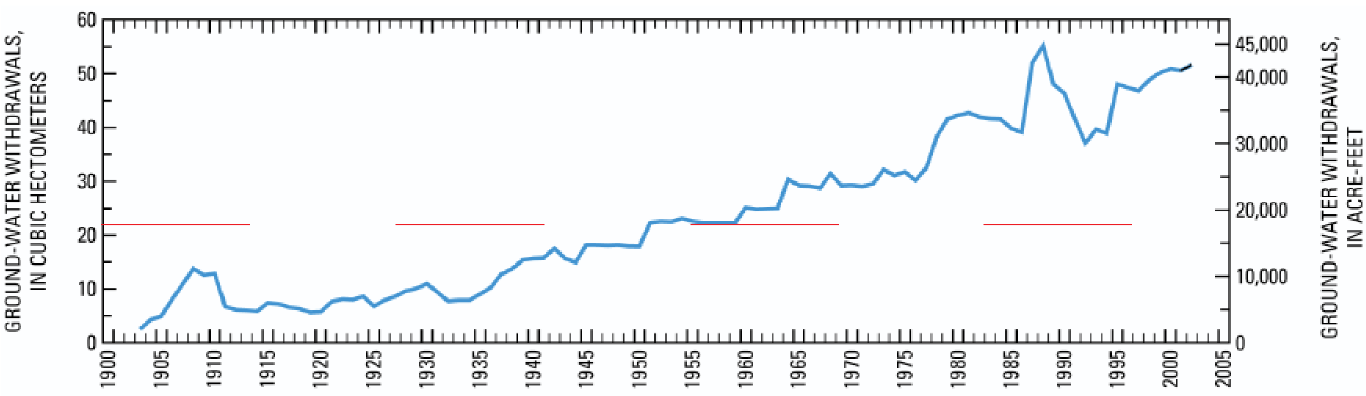


Figure 4: Annual groundwater withdrawal rates, 1902-2002, Upper San Pedro Basin, Arizona. The red dashed line represents approximate annual recharge. (Source: Pool and Dickinson 2006)

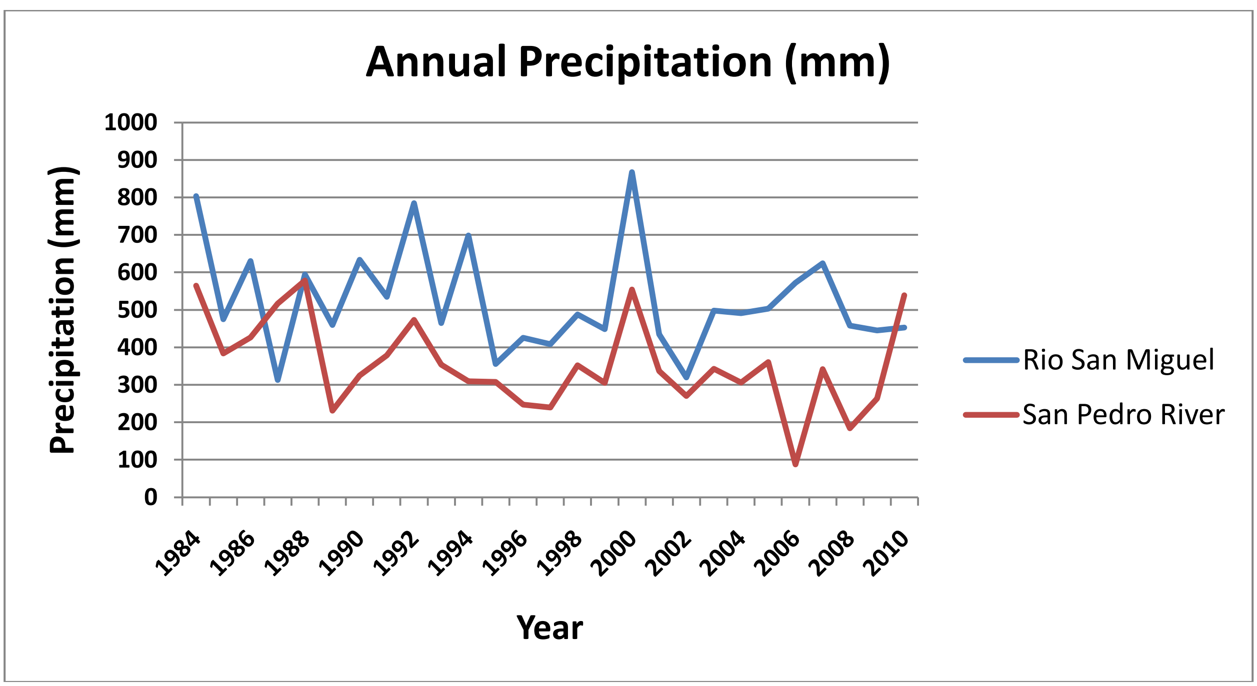


Figure 5: Annual precipitation (1984-2010) in the Upper San Pedro and Rio San Miguel watersheds.

Figure 6: (Left) Pre-1984, grazing was permitted in the riparian area. (Right) Post-1997, due to the SPRNCA designation, riparian vegetation recovery has occurred in some reaches of the river. (Source: Brookshire et al. 2010)

*Rio San Miguel*

The Rio San Miguel flows from Northern Sonora, near the headwaters of the San Pedro River, south to the city of Hermosillo where it joins with the Rio Sonora before draining into the Sea of Cortez (Figure 1). Water is scarce in the Rio San Miguel watershed, which limits irrigation, but sustains floodplain agriculture. Interestingly, Nabhan and Sheridan (1977) found that farmers in the floodplains of the Rio San Miguel rely on the riparian forest, mainly the willow and cottonwood trees, to increase their resilience to floods. The riparian vegetation provides the farmers with many services, including retarding channel cutting, limiting erosion, and trapping floodwater sediment. The terrain surrounding the Rio San Miguel is mountainous, the valley is narrow, and the influence of the North American monsoon (NAM) is strong with 60 to 75% of precipitation falling between July and September. Mendez-Barroso et al. (2009) found a strong degree of coupling between vegetation greening and hydrologic conditions throughout the Rio San Miguel basin.

**4. Data and Methods:**

For this research, we utilized a time series of four Landsat TM (Thematic Mapper) images for the 20-year period 1990-2010, monthly precipitation data from stations in the San Pedro and Rio San Miguel basins, and ancillary Geographic Information Systems (GIS) data layers. To cover both the Upper Rio San Miguel and the Upper San Pedro River it was necessary to collect imagery from two scenes, path 35, rows 38 and 39. The dates of the images are as follows: May 4, 1990; October 11, 1990; May 15, 1994; October 22, 1994; (Table 1).

Table 1: Landsat scene dates and locations

| **Year** | **Path 35, Row 38** | **Path 35, Row 39** |
|---|---|---|
| **1984** | May 3 | May 3 |
| **1990** | May 4<br>October 11 | May 4<br>October 11 |
| **1994** | May 15<br>October 22 | May 15<br>October 22 |
| **1999** | May 13<br>October 4 | May 13<br>October 4 |
| **2005** | May 13<br>October 20 | May 13<br>October 20 |

| 2010 | May 11<br>October 2 | May 11<br>October 2 |
|---|---|---|

Unfortunately, in 1999, all three scenes were not available from the same date, thus the use of May 29 for path 35, row 38 and May 13 for path 35, row 39 and 40. Landsat TM imagery has 7 spectral bands (including the visible, NIR, SWIR, and thermal IR portions of the electromagnetic spectrum), a moderate spatial resolution of 30 meters, and a moderate temporal resolution of about 16 days. As discussed in the Literature Review (section 2), there are disadvantages to using a moderate spatial resolution sensor for research in riparian corridors, due to the narrow width of the area. However, in this research we seek to examine change in overall vegetation cover, not fine-scale riparian vegetation structure. Landsat also has the advantages of being free, easily accessible to the public through the USGS website, and is pre-processed to a level 1 product, which is calibrated and geometrically orthorectified, though not atmospherically corrected.

After acquiring the Landsat imagery from the USGS, we used ERDAS to process the images and ArcMap 9.3 to spatially analyze the NDVI data, based on two riparian corridors. First, due to needing two scenes to cover the study area, we used ERDAS to mosaic each set of three images together. We used the Model Maker function of ERDAS to run an NDVI analysis for each image mosaic. For each set of dates (1990 and 1994; 1994 and 1999; 1999 and 2005; and 2005 and 2010), we produced inter-annual and intra-annual NDVI change detection images.

**5. Land Cover Change Results**

The results of the NDVI analysis provide insight into the vegetation dynamics, influenced by a unique mixture of natural and anthropogenic processes and drivers, in each of the riparian systems as well as the broader watersheds. Overall, the analysis shows consistently higher levels of greenness in the San Miguel riparian corridor than the San Pedro riparian corridor across all years and seasons we examined (Figure 7 and Table 2). Water availability from surface and base flow are major determinants of riparian vegetation presence, diversity, and composition. The type and amount of water available in arid region riparian systems varies by season due to influences from both natural precipitation variability and recharge processes and human influences of surface water diversion and groundwater pumping for agricultural, urban, and industrial (ie. mining) activities. As described in the Study Area (Section 3), the precipitation regime, namely the North American Monsoon (NAM), although an important source of water for both systems, is experienced more intensely in the San Miguel watershed than the San Pedro watershed where the average June to October precipitation from 1984 to 2010 is 397.4 mm and 246.4 mm, respectively. Additionally, the type, location, and intensity of water-intensive activities differ between the two basins. These differences are reflected in the inter- and intra-annual NDVI change analyses (Tables 3 and 4) in terms of the amount of variation detected at each spatial scale and the correlation between monsoon-precipitation dominated greenup and anthropogenic activities, such as crop irrigation.

Table 2: NDVI mean values

| | May 1984 | May 1990 | Oct. 1990 | May 1994 | Oct. 1994 | May 1999 | Oct. 1999 | May 2005 | Oct. 2005 | May 2010 | Oct. 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **San Pedro Watershed** | 0.106 | 0.055 | 0.174 | 0.063 | 0.128 | 0.042 | 0.149 | 0.079 | 0.127 | 0.1 | 0.157 |
| **SPRNCA** | 0.089 | 0.03 | 0.15 | 0.035 | 0.134 | 0.034 | 0.154 | 0.051 | 0.144 | 0.054 | 0.158 |
| **San Pedro 1 KM** | 0.124 | 0.068 | 0.173 | 0.075 | 0.147 | 0.07 | 0.164 | 0.1 | 0.162 | 0.091 | 0.195 |
| **San Pedro 5 KM** | 0.093 | 0.037 | 0.139 | 0.044 | 0.11 | 0.032 | 0.122 | 0.066 | 0.116 | 0.072 | 0.14 |
| **San Miguel Watershed** | 0.143 | 0.081 | 0.321 | 0.123 | 0.203 | 0.054 | 0.237 | 0.131 | 0.2 | 0.136 | 0.364 |
| **San Miguel 1 KM** | 0.151 | 0.097 | 0.293 | 0.099 | 0.182 | 0.071 | 0.21 | 0.131 | 0.186 | 0.137 | 0.326 |
| **San Miguel 5 KM** | 0.13 | 0.072 | 0.307 | 0.072 | 0.179 | 0.047 | 0.206 | 0.113 | 0.179 | 0.116 | 0.343 |

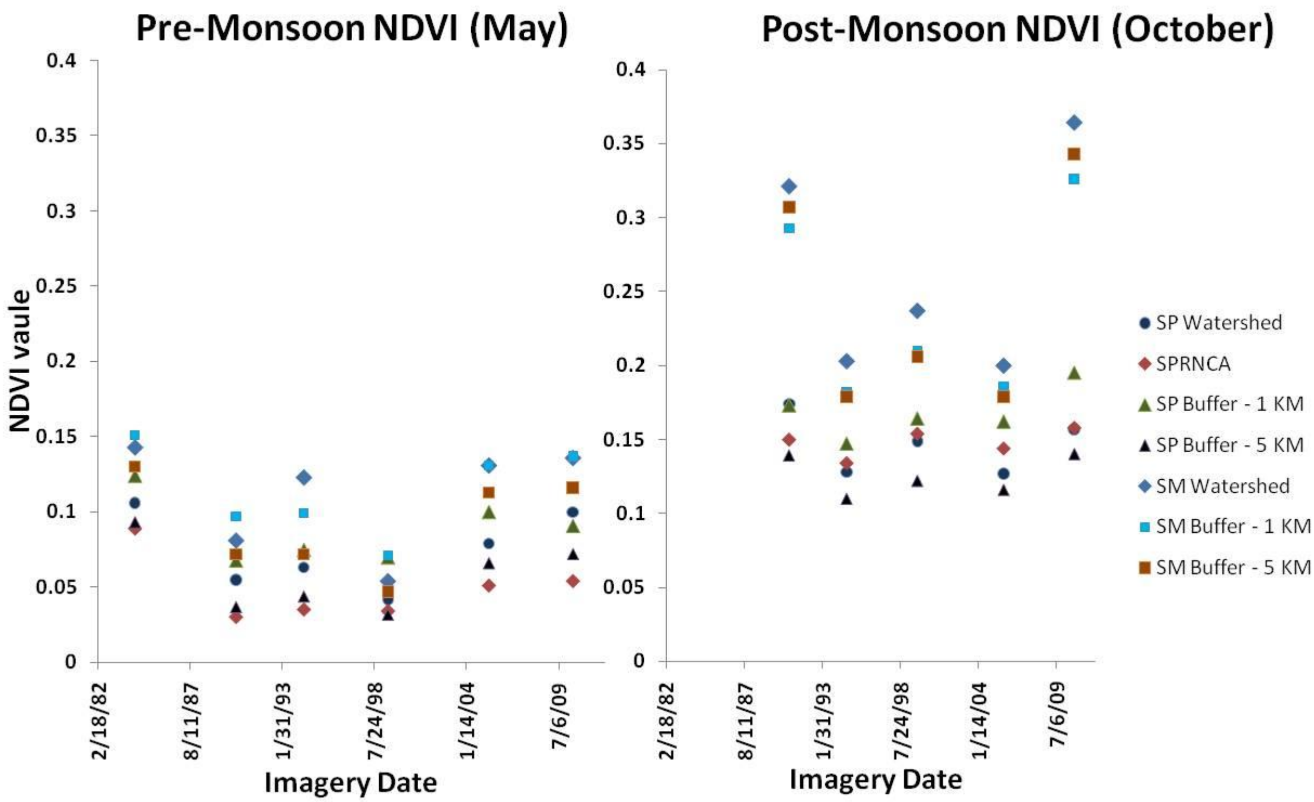


Figure 7: NDVI values for the multiple spatial scales of analysis for the pre-monsoon imagery, obtained in May (1984-2010), and the post-monsoon imagery, obtained in October (1990-2010)

Table 3: Inter-Annual NDVI Change

| | May to Oct. 1990 | May to Oct. 1994 | May to Oct. 1999 | May to Oct. 2005 | May to Oct. 2010 |
|---|---|---|---|---|---|
| **San Pedro Watershed** | 0.119 | 0.065 | 0.107 | 0.048 | 0.061 |
| **SPRNCA** | 0.12 | 0.099 | 0.12 | 0.094 | 0.104 |
| **San Pedro 1 KM** | 0.105 | 0.072 | 0.094 | 0.062 | 0.104 |
| **San Pedro 5 KM** | 0.102 | 0.066 | 0.09 | 0.049 | 0.068 |
| **San Miguel Watershed** | 0.24 | 0.123 | 0.183 | 0.068 | 0.228 |
| **San Miguel 1 KM** | 0.196 | 0.084 | 0.139 | 0.055 | 0.189 |
| **San Miguel 5 KM** | 0.235 | 0.108 | 0.09 | 0.066 | 0.227 |

Table 4: Intra-Annual NDVI Change

| | May 84-90 | May 90-94 | May 94-99 | May 99-05 | May 05-10 | Oct. 90-94 | Oct. 94-99 | Oct. 99-05 | Oct. 05-10 |
|---|---|---|---|---|---|---|---|---|---|
| **San Pedro Watershed** | -0.051 | 0.009 | -0.021 | 0.037 | -0.017 | -0.938 | 0.021 | -0.022 | 0.03 |
| **SPRNCA** | -0.059 | 0.005 | -0.001 | 0.017 | -0.004 | -0.016 | -0.022 | -0.01 | 0.014 |
| **San Pedro 1 KM** | -0.056 | 0.006 | -0.005 | 0.03 | 0.009 | -0.026 | 0.017 | -0.002 | 0.033 |
| **San Pedro 5 KM** | -0.056 | 0.007 | -0.012 | 0.034 | -0.006 | -0.029 | 0.012 | -0.007 | 0.025 |
| **San Miguel Watershed** | -0.062 | -0.001 | -0.026 | 0.077 | -0.004 | -0.117 | 0.034 | -0.038 | 0.164 |
| **San Miguel 1 KM** | -0.054 | 0.002 | -0.028 | 0.06 | -0.006 | -0.111 | 0.027 | -0.024 | 0.14 |
| **San Miguel 5 KM** | -0.058 | 0 | -0.024 | 0.066 | -0.003 | -0.127 | 0.026 | -0.027 | 0.164 |

Floodplain agriculture exists within the 1 km and 5 km riparian boundaries of the Rio San Miguel. With the exception of the small towns of Rayon and Cucurpe, the majority of human water withdrawal – both surface water diversion and groundwater pumping – and subsequent water application, through irrigation, is to support agricultural and ranching activities. The existence of human influence in the riparian buffer zones of the Rio San Miguel helps to explain the weak correlations between June to October (an approximation of the monsoon) precipitation and NDVI values in the post-monsoon imagery (Table 5). The weak correlation ($R^2$ below 0.2 for all three spatial scales of analysis) in the San Miguel riparian SES suggests that other factors are strong determinants of NDVI, such as the crop phenology, irrigation, harvest timing, grazing patterns, and water available to riparian vegetation from base flow sources.

Table 5: $R^2$ values for the scatterplot (Figure 8) showing the relation between precipitation and NDVI values for the multiple spatial scales of analysis for the pre-monsoon (precipitation defined as January to May) and the post-monsoon (precipitation defined as June to October).

| | Pre-Monsoon scatterplot $R^2$ values | Post-Monsoon scatterplot $R^2$ values | Combined pre- and post-monsoon scatterplot $R^2$ values |
|---|---|---|---|
| **San Pedro Watershed** | 0.609 | 0.144 | 0.77 |
| **SPRNCA** | 0.196 | 0.812 | 0.748 |
| **San Pedro 1 KM** | 0.192 | 0.643 | 0.774 |
| **San Pedro 5 KM** | 0.409 | 0.362 | 0.772 |
| **San Miguel Watershed** | 0.446 | 0.198 | 0.759 |
| **San Miguel 1 KM** | 0.463 | 0.197 | 0.737 |
| **San Miguel 5 KM** | 0.515 | 0.196 | 0.751 |

In contrast, the San Pedro watershed is more highly urbanized and intensively populated and supports a more diverse set of activities, including large mining operations, agriculture, ranching, military forts, and federally designated conservation and recreation areas. Overall NDVI is markedly lower in the San Pedro riparian SES in both the pre- and post-monsoon imagery (Figure 7 and Table 2). Interestingly, the SPRNCA and 1 km riparian buffer of the San Pedro River, which overlap in some areas (Figure 2), have weak pre-monsoon correlations between precipitation and NDVI (0.196 and 0.192, respectively) but exhibit strong post-monsoon correlations (0.812 and 0.643, respectively) (Figure 8 and Table 5).

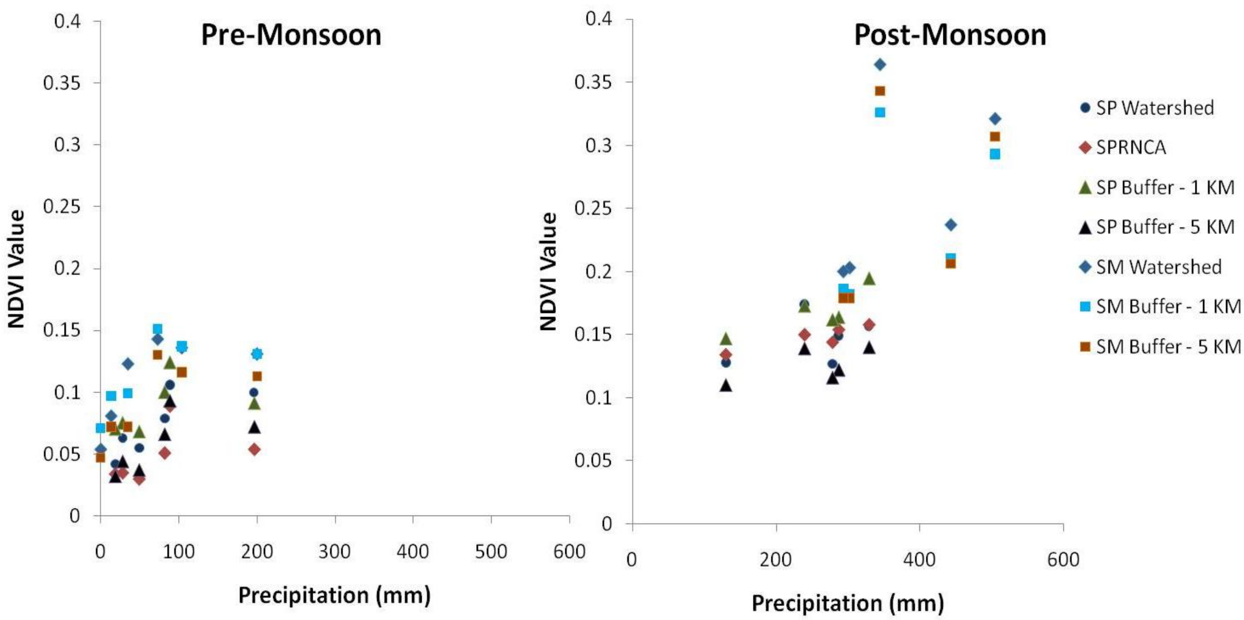


Figure 8: Scatterplot showing the relation between precipitation and NDVI values for the multiple spatial scales of analysis for the pre-monsoon (precipitation defined as January to May) and the post-monsoon (precipitation defined as June to October).

The designation of the SPRNCA in 1988 and the regulations on water consumption related to the United States Endangered Species Act (ESA) has limited human activity within the SPRNCA boundary and the most proximate riparian buffer. The removal of agriculture and grazing from the riparian area helps to explain the strong influence of the natural monsoon precipitation regime on the vegetation dynamics, as surface water is neither being diverted within the alluvial plain nor is irrigation water being applied. In the pre-monsoon period, other factors serve as important determinants of vegetation presence and composition, including urban runoff and engineered groundwater recharge basins, designed to mitigate the negative impacts of previous intensive water extraction. However, at the broad San Pedro watershed scale, the pattern is reversed reflecting that of the Rio San Miguel; the pre-monsoon correlation is strong (0.609) and the post-monsoon correlation is weak (0.144). At this spatial scale, the range of diverse activities and livelihoods being supported in the basin exerts influence on the large-scale vegetation dynamics, including vegetation clearing as result of intensive copper mining in Cananea, impacts from wildfires, continuing urbanization, and agricultural and grazing practices.

**6. Discussion: Arid Region Riparian Resilience, Ecosystem Service Provision, and Tradeoffs under a Range of Conditions**

Changes in riparian SES conditions range from primarily natural to predominantly anthropogenic (Table 6). Here, we examine hypothesized impacts to ecosystem service provisions from an arid region riparian SES at either extreme of a range of conditions that span the gradient from natural to anthropogenic influence. Through this discussion, we highlight how land use and land cover change analysis, such as NDVI change analysis, can serve as an important source of data for examining changes to ecosystem services that have already occurred and hypothesizing potential changes under alternative future scenarios. The Millennium Ecosystem Assessment report identifies four types of ecosystem services: 1) provisioning services, which provide products such as fresh water, food, fiber, and fuel, 2) regulating services, which include regulation of climate, erosion, natural hazards, pollution, and hydrologic flows, 3) cultural services, which are nonmaterial benefits, including sources of inspiration, aesthetic values, opportunities for recreational activities, and educational value, and 4) supporting services, such as sediment retention, accumulation of organic matter, and the storage, recycling, processing and acquisition of nutrients (MA 2005).

Table 6: Condition, system state and hypothesized impact on four categories of arid riparian SES ecosystem services: provisioning services, regulating services, supporting services, and cultural services (up arrow indicates hypothesized increase in provisions, straight line indicates hypothesis of no change in provisions, and down arrow indicates hypothesized decrease in provisions)

| | **Condition** | **System State** | **Provisioning Services** | **Regulating Services** | **Supporting Services** | **Cultural Services** | **Multi-sectoral Tradeoffs** |
|---|---|---|---|---|---|---|---|
| **Natural** | Winter rain dominance of annual precipitation decreases | • Flow regime in river<br>• ESA litigation | ↔ | ↓ | ↓ | ↓ | Low |
| ↑ | Annual precipitation overall decreases | • Flow regime in river<br>• Riparian ground water<br>• ESA litigation | ↓ | ↓ | ↓ | ↓ | Medium |
| | Mesquite cover increases | • Grassland cover<br>• Transpiration increases | ↔ | ↓ | ↔ | ↔ | Low |
| | Riparian groundwater levels decreases | • Mesquite vs. Cottonwood /Willow cover<br>• Species richness | ↓ | ↓ | ↓ | ↓ | Medium |
| | Urban cover in the watershed increases | • Groundwater levels decline<br>• Surface runoff increases | ↓ | ↓ | ↓ | ↓ | High |
| ↓ | Increased water use by Cananea Mine | • Flow regime in river<br>• Water quality | ↓ | ↓ | ↓ | ↓ | High |
| | Fort H. closes or missions are reduced | • Flow regime in river<br>• Groundwater levels increase | ↑ | ↑ | ↑ | ↑ | High |
| **Anthropogenic** | Water Supply Augmentation to Sierra Vista and SPRNCA | • Flow regime in river<br>• Groundwater levels increase | ↑ | ↑ | ↑ | ↑ | High |

Changing conditions, whether driven by natural or anthropogenic processes, affect SES resilience. As a SES reorganizes in an alternate system state, after passing a threshold, system properties, parameters, content, and processes change altering the range of ecosystem services that can be provided. Decisions concerning the utilization and management of the environment involve tradeoffs across sectors and stakeholders that impact the provisioning of certain classes of ecosystem services. Although the ecosystem services themselves are the material benefits that are most evident for societal use, it is important to focus on impacts to the underlying processes (ie. resource availability and flood dynamics (White and Stromberg 2011)) and mechanisms that result in the desired set of ecosystem services, as it is this functionality that is altered as a SES crosses a threshold into an alternative system state (Ernston et al. 2010).

*Primarily Natural Condition*

A primarily natural driver of change in the arid region riparian system state is the noted decrease in winter rain dominance of annual precipitation, which impacts the fundamental processes of resource distribution and winter flooding through which a keystone riparian tree species, the cottonwood, propagates. Decreasing winter precipitation and an almost 30-year gap between winter flood pulses has impacted the resilience of the San Pedro riparian SES and altered vegetation dynamics by impeding seed transportation and reducing small-scale disturbances important for maximizing diversity by removing biomass and redistributing resources (White and Stromberg 2011).

Two important properties of the system state are the river flow regime, historically characterized by bi-annual flood events during heavy precipitation in the summer and winter months, and the U.S. Endangered Species Act (ESA), which is a highly contested institutional regime that has been leveraged by certain stakeholders to protect a bundle of preferred ecosystem service provisions. In the case of crossing a critical threshold into an alternate state of decreased winter precipitation, we hypothesize that regulating, supporting, and cultural ecosystem service provisions would decline, while provisioning services may not be affected. More specifically, the ecosystem service provisions likely to decrease are hydrologic flow regulation, including groundwater recharge, water purification through removal of excess nutrients, erosion regulation, flood control, and nutrient cycling, due to plant community change. Loss of bird diversity – the San Pedro River is a major inter-continental flyway for bird migration – would have negative impacts for pollination and recreational, aesthetic, and educational service provisions. In contrast, at least within the SPRNCA, reliance on provisioning services from the riparian system, such as food, water, fiber, and fuel, has been in decline due to legally-mandated ESA regulations and institutional decision-making that has sought to increase the adaptive capacity of the riparian SES by limiting extractive resource use, hence the hypothesis of no-change in terms of provisioning services.

The NDVI analysis data contributes interesting, though at first glance, paradoxical information in relation to the changes in riparian resilience described above. Focusing on the San Pedro River, in the SPRNCA and the 1 km riparian buffer, both pre- and post- monsoon NDVI declined in the period directly following the designation of the SPRNCA in 1988, during which time irrigated agriculture was removed from the riparian area, thus removing a strong vegetation signal. However, since the early 1990s, pre-monsoon NDVI exhibits a slightly increasing trend, which seems to contradict the expected result of the decreasing winter precipitation over the same period. However, a possible explanation for the divergent evidence is the strong NDVI signal from the mature cottonwood forest that has established along the river bank over the previous 3 decades without major flood disturbance. Changing riparian vegetation community composition, characterized by mesquite encroachment also helps to explain the increase in NDVI. In this case, although NDVI suggests increased vegetation presence, the composition and structure of the vegetation is more closely linked to the underlying processes and mechanisms that ultimately influence the resilience of the SES.

*Predominantly Anthropogenic Condition*

A potential future anthropogenic driver of change in the arid region riparian system state in the San Pedro watershed is a plan to augment available water resources for the most urbanized portion of the basin, through a range of alternatives, most notably, the extension of the Central Arizona Project (CAP) canal infrastructure, which currently carries Colorado River water as far south as Tucson, Arizona. The Sierra Vista sub-watershed of the San Pedro River contains two important assets, the SPRNCA and the U.S. Army's Fort Huachuca. Decades of urban development in the Sierra Vista sub-watershed has resulted in increased groundwater pumping and more recently in substantial groundwater overdraft that negatively impacts the surface water level in the San Pedro River.

In 1998, the Upper San Pedro Partnership (USPP), a consortium of 21 Federal, State, local and private agencies and organizations, was established to manage – and though not explicitly stated, to enhance – the adaptive capacity of the SES with the stated mission to meet the long-term water needs of the Sierra Vista sub-watershed by achieving sustainable yield of the regional aquifer by 2011. Interestingly, meeting the goal of sustainable yield has become dominant in the institutional discourse, purposefully conflated with (what might otherwise seem two divergent goals): 1) the preservation of the ecosystem services provided by the SPRNCA, in particular the legally mandated protection of vital habitat for the endangered Huachuca water umbel, and 2) the guarantee of long-term viability for Fort Huachuca, the largest employer in the area. The U.S. Bureau of Reclamation (BOR) has become a powerful player in the process of vetting potential water augmentation alternatives, first suggesting that the USPP enter into a planning process to develop a list of alternatives, and now taking on the role of analyzing the alternatives to determine their feasibility. The USPP-BOR jointly written goal of the augmentation project, creates an institutional framework that inherently privileges large-scale, supply-side engineering solutions, stating that, “A set of *water augmentation solutions* is needed that …would supplement existing and future recharge, reuse, conservation, and other water resource management solutions implemented in the Sub-watershed” (BOR, 2007). This discourse serves to dismiss demand-side alternatives, such as reuse and conservation, as side projects rather than as legitimate solutions to the problem.

In terms of ecosystem service provisions, we hypothesize that the proposed flow augmentation alternative that would extend the CAP to the Sierra Vista sub-watershed would superficially, and primarily in the short-term, increase all four of the ecosystem service provision categories (Table 6). The flow augmentation plan would serve to increase groundwater levels through increased levels of recharge, affecting the amount and timing of baseflow available to the riparian vegetation community. Depending on the spatial and temporal specificities of plans to release water directly into the surface flow of the river, the flow augmentation would also impact the flow regime of the San Pedro River, potentially returning some ephemeral reaches to perennial status, with continuous, year-round surface flow.

However, the tradeoffs, between stakeholders and sectors, are inherently high in this type of large-scale environmental engineering plan, and over the long-term are likely to actually diminish the adaptive capacity and erode the resilience of the riparian SES by strengthening positive feedbacks and establishing maladaptive, energy-intensive pathways that encourage consumption, rather than focus on limits (Robards et al. 2011). In resilience theory, positive feedbacks are conceptualized as processes and structures that mutually reinforce one another, sustaining and stabilizing path-dependent regimes, which both shape and govern system dynamics (Ernston 2010). These structuring processes are theorized to create systems that are far from equilibrium and are characterized by higher uncertainty and vulnerability to crossing thresholds. The Millennium Ecosystem Assessment also suggests to align response options with the level of governance where they can be most effective, thus, local response options will be more effectively governed through local institutions. When viewed through the lens of sustaining economic growth as the primary driver, which is dependent on continued groundwater reliance, the provisioning service (in this case, water extraction) is being prioritized over the regulating, supporting, and cultural services (Robards et al. 2011), many of which are legitimized in local political discourse solely because their protection is legally mandated through the ESA regulations.

As a hypothetical future condition, we are limited to hypothesizing the impact of the CAP extension project on the NDVI response and vegetation dynamics in the riparian SES. An analysis of a flow restoration project on the highly urbanized Salt River, found that stream reaches that received surface water allocations (primarily composed of effluent) rebounded in terms of plant presence, community, and composition (White and Stromberg 2011). The authors contend that high sediment concentration in the effluent and the ability to restore small flood pulses to mimic the natural flow regime served to re-establish the fundamental underlying processes in the riparian system, leading to enhanced ecosystem service provisions. In the case of the CAP extension, the water would not contain the high nutrient content of the effluent and would primarily be recharged to the groundwater to mitigate the cone of depression under the City of Sierra Vista, thus by-passing most direct surface flow influence. Research is finding that the timing and location of groundwater recharge impacts where responses are seen, dependent on the local geology and groundwater circulation dynamics present. Thus, it is possible that any NDVI response would be spatially and temporally patchy, if even evident through remotely sensed imagery. The amount of time between engineered groundwater recharge and riparian vegetation response is also complex and may prove difficult to monitor.

## 7. Conclusion

This research is part of a larger five-year project to investigate the coupled human and natural dynamics of Sonora Desert riparian ecosystems. We examine how the processes of land use and land cover change in two arid region border watersheds, the US-Mexico bi-national San Pedro River and the Rio San Miguel, located in Sonora, Mexico, affect vegetation patterns in riparian SES. We contribute to resilience theory by using NDVI vegetation change information to hypothesize impacts of changing conditions on system states in relation to thresholds and assess the impact of crossing into an alternative system state on four classes of ecosystem service provisions. We find that NDVI information can assist in explaining seemingly contradictory vegetation responses in riparian systems, especially in arid regions, where vegetation dynamics naturally rely on seasonal flood pulses for nutrient redistribution, small-scale distribution and propagation, but are increasingly impacted by anthropogenic activities, such as irrigation, which impact flow regimes. The particular bundle of ecosystem service provisions that are prioritized at a specific point in time in a specific place differ, depending on institutional factors, including legally mandated obligations, positive feedbacks and maladaptive path dependence, but tend to prioritize provisioning services over regulating, supporting, and cultural services.

We use this conceptual framework to interrogate two specific conditions, the decrease in winter rain dominance of annual precipitation and the hypothetical water supply augmentation project to extend the CAP to the Sierra Vista watershed of the San Pedro River. Short-term impacts of these conditions on ecosystem service provisions may obscure the long-term effects to riparian resilience, with human management likely to prioritize short-term gains and emphasis on growth and consumption, over long-term gains and focus on limits. Riparian vegetation dynamics are both spatially and temporally heterogeneous, themes that we were only able to superficially discuss in this paper, but will be the focus of future analysis of riparian resilience.

**Acknowledgements**

This material is based upon work supported by the National Science Foundation (NSF, Grant DEB-1010495) and the Inter-American Institute for Global Change Research (IAI) project SGP-HD #005 (supported by NSF Grant GEO-0642841).

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