Effluent-Dominated Waterways in the Southwestern United States:

Advancing Water Policy through Ecological Analysis

by

Margaret Susan White

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved November 2011 by the
Graduate Supervisory Committee:

Juliet C. Stromberg, Chair
Stuart G. Fisher
Jianguo Wu
Dave White
James Holway

ARIZONA STATE UNIVERSITY

December 2011

ABSTRACT

Over the past century in the southwestern United States human actions have altered hydrological processes that shape riparian ecosystems. One change, release of treated wastewater into waterways, has created perennial base flows and increased nutrient availability in ephemeral or intermittent channels. While there are benefits to utilizing treated wastewater for environmental flows, there are numerous unresolved ecohydrological issues regarding the efficacy of effluent to sustain groundwater-dependent riparian ecosystems. This research examined how nutrient-rich effluent, released into waterways with varying depths to groundwater, influences riparian plant community development. Statewide analysis of spatial and temporal patterns of effluent generation and release revealed that hydrogeomorphic setting significantly influences downstream riparian response. Approximately 70% of effluent released is into deep groundwater systems, which produced the lowest riparian development. A greenhouse study assessed how varying concentrations of nitrogen and phosphorus, emulating levels in effluent, influenced plant community response. With increasing nitrogen concentrations, vegetation emerging from riparian seed banks had greater biomass, reduced species richness, and greater abundance of nitrophilic species. The effluent-dominated Santa Cruz River in southern Arizona, with a shallow groundwater upper reach and deep groundwater lower reach, served as a study river while the San Pedro River provided a control. Analysis revealed that woody species richness and composition were similar between the two systems. Hydric pioneers (*Populus fremontii*, *Salix gooddingii*) were dominant at perennial sites on both rivers. Nitrophilic species (*Conium maculatum, Polygonum lapathifolium)* dominated herbaceous plant communities and plant heights were greatest in effluent-dominated reaches. Riparian vegetation declined with increasing downstream distance in the upper Santa Cruz, while patterns in the lower Santa Cruz were confounded by additional downstream agricultural input and a channelized floodplain. There were distinct longitudinal and lateral shifts toward more xeric species with increasing downstream distance and increasing lateral distance from the low-flow channel. Patterns in the upper and lower Santa Cruz reaches indicate that water availability drives riparian vegetation outcomes below treatment facilities. Ultimately, this research informs decision processes and increases adaptive capacity for water resources policy and management through the integration of ecological data in decision frameworks regarding the release of effluent for environmental flows.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor, Dr. Juliet C. Stromberg. She has consistently provided new ideas, challenged perspectives, and opened landscapes. Through her guidance I have grown intellectually, scientifically, and professionally.

I also owe great appreciation to Dr. Dave White, Dr. Jianguo Wu, and Dr. James Holway for their support, expertise, and guidance through the entire process. Dr. Stuart Fisher has been steadfast in his encouragement, candor, and feedback, which only strengthened my work.

Thank you to the entire Stromberg lab for field and greenhouse assistance, comments and opinions, baked goods, and moral support: Melanie Tluczek, Jackie Betsch, Andrea Hazelton, Danika Setaro, Amanda Suchy, and Lane Butler. I would especially like to thank Natalie Case, my partner in crime on the Santa Cruz and in keeping me vertical into the wee hours.

Of course I have to thank my family. Thank you to my parents for providing me with words of encouragement and understanding when airwaves went silent for far too long. Tim and Jen have provided constant assistance and kept me grounded throughout this entire journey. Chad has been unwavering in his support and ability to push my cognitive development. Beth reminds me there is more to life - like laughter. You all make me better. I love you.

Without my friends, I would be much more unbalanced than I already am. You know who you are – and I hope you always do. Always.

Finally, I would like to thank Jeremy - my coach, beard and best friend. Your patience, love, support, strength, and hugs have helped me maintain my sanity. You’re my favorite.

My research has been funded by several sources. I secured three years of support through the Environmental Protection Agency's Science-To-Achieve-Results (EPA STAR) fellowship program, for which I am very grateful. The United States Army Corps of Engineers funded a research proposal to study multiple rivers in the state of Arizona, and my work was inspired from those field studies. Finally, the School of Life Sciences also provided financial support and travel funds that furthered my professional development.

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1. INTRODUCTION

Over the past century in the southwestern United States, rapid economic growth, expanding urban centers and agriculture have driven steep increases in freshwater demands, which have been met through groundwater pumping, surface flow diversions, and dams - all of which alter water availability and flow patterns in rivers (Sala et al., 2000). These shifting baseline conditions combined with episodic drought, have led to the drying of river reaches that were once perennial and a decline in the extent of riparian habitat from historical coverage (Logan, 2002; Lite and Stromberg, 2005; Webb and Leake, 2006). While development and consumption patterns have impacted groundwater resources available to riparian ecosystems, these patterns have also produced treated wastewater, or effluent, much of which historically has been discharged into nearby river channels. This dynamic has led to the emergence of effluent-dominated waterways, or rivers that derive a large percentage of their surface flows from the daily production and release of effluent into a stream channel (Brooks *et al*., 2006).

Treated wastewater, or effluent, has become an increasingly important component of the freshwater landscape, particularly in more water-limited regions (Bouwer, 2002). Today, effluent is a potential water resource for the restoration and maintenance of riparian systems. However, effluent-dominated systems are fundamentally different from the intermittent or ephemeral streams they displace. Numerous ecohydrological issues have emerged concerning the influence of effluent on riverine ecosystems and their associated riparian plant communities. For example, the introduction of treated wastewater into a stream can alter stream flow sufficiently to change the composition of the riparian community (Marler *et al.*, 2001; Brooks *et al.*, 2006). The hydrogeomorphic setting into which the effluent is released can also dictate the degree to vegetation is restored within the multiple zones that comprise a riparian corridor. Increased nutrient levels in treated wastewater may bolster vegetation growth but can also lead to changes in plant species composition and dominance, leading to a reduction in species richness (Craine *et al.,* 2002; Mathewson *et al.,* 2003; Verhoeven *et al.,* 2006). High nitrogen levels can also foster biological activity within the channel that can lead to the formation of clogging layers in surface sediments which can act as a seal the bottom of the stream channel, decreasing infiltration and recharge and hindering the connection between surface water, subflow, and groundwater, changing conditions for phreatophytic plants (Lacher, 1996; Brunke and Gonser, 1997; Boulton *et al.*, 1998).

Ensuring that treated wastewater contributes to, rather than degrades, riparian function hinges on an understanding of riparian plant community response to hydrological dynamics and water quality impacts in various hydrogeomorphic settings. While there are many benefits to utilizing effluent for riparian ecosystem restoration, there is little knowledge about how riparian plant communities respond to long-term, continuous release of effluent. Ultimately, lack of understanding about the dynamics of effluent-dominated streams underscores the growing need for suitable methods to evaluate the ecological integrity of these systems (Brooks *et al.*, 2006).

This knowledge gap is particularly compelling within the context of water scarcity, the call for increased water reuse in arid and semi-arid regions, and the need for integrated water resources management. In the absence of historical policy precedent or planning practice, the shift from ephemeral to perennial stream flows poses new challenges for both the scientific and planning communities. Existing water policies may be insufficient to address these problems, and decision makers lack adequate scientific models to develop new programs or standards. Currently, resource managers must resort to a patchwork of borrowed practices based on historical ecosystems or imported models from different regions. Uncertainties about the ecological effects of increased nutrient loads and hydrologic variability on the establishment of riparian plant communities along effluent-dominated waterways call for research to improve water resources planning and management through scientific analysis (Duran and Spencer, 2004; White et al., 2007).

The main objectives of this research were to assess riparian vegetation response in effluent-dominated waterways and provide insight into the potential use of effluent to restore or enhance riparian ecosystems. To accomplish these goals, this dissertation is organized into four chapters. In Chapter 1, we assessed opportunities and challenges in securing effluent for riparian ecosystem restoration given current water policy frameworks. This work was divided into two parts: an analysis of the history of water policy and management in Arizona and spatial analysis of riparian habitat development on effluent-dominated waterways to inform recommendations for integrated water resources management. Chapter 2 was a greenhouse experiment investigating how streamside herbaceous communities from varying hydrologic settings (ephemeral, perennial, effluent-dominated) responded to nutrient-rich effluent. Specifically, we quantified the influence of perennial effluent flows, with associated elevated nitrogen and phosphorus concentrations, on riparian plant community composition and biomass. Using the effluent-dominated Santa Cruz

River as a study river, Chapters 3 and 4 were designed to compare woody and herbaceous riparian plant communities between an effluent-dominated riparian ecosystem with a shallow water table (Upper Santa Cruz reach), an effluent-dominated riparian ecosystem with a deep water table (Lower Santa Cruz reach), and a non-effluent control (San Pedro River). Further, we examined plant community patterns with distance downstream from effluent outfall points (longitudinal analysis) and contrasted zonal patterns among river types (lateral analysis) across spatial and temporal scales.

2. UNCERTAIN WATERS: THE ROLE OF WATER POLICY AND SCIENCE IN EFFLUENT RELEASE AND RIPARIAN ECOSYSTEM RESTORATION

ABSTRACT

Increasing freshwater demands coupled with concerns over water scarcity have resulted in an intense and complex conflict between the development of rivers as water and energy sources, and their conservation as biologically diverse, integrated ecosystems. Nowhere is this conflict more apparent than in Arizona, where the continued support and survival of expanding urban and rural areas depend greatly on what choices are made regarding water management, including the maintenance of agriculture and other industries, and sufficient future environmental and riparian protection. It has become increasingly evident that established water policies under the current laws and management regimes do not have the inherent adaptive capacity needed to address the challenges facing water demand in the 21st century. Yet Federal and state approaches to water legislation remain somewhat fragmented and limited institutional and policy steps have been taken to develop new tools and approaches addressing these challenges. The lack of clear, reliable data on wastewater generation has led to a serious gap in knowledge regarding water reuse and environmental needs in Arizona. Spatial and temporal analyses of wastewater treatment, effluent generation, and release revealed that that hydrogeomorphic setting significantly influences downstream riparian response. Current practice has just under 50% of effluent generated released into nearby channels or waterbodies. Additional analysis showed that approximately 70% of sampled discharge points released effluent into ephemeral or deep groundwater systems. These scientific outputs inform recommendations which include the

need to recognize riparian habitat as beneficial use for instream flows, develop criteria specific to effluent dominated waterways, and increased adaptive capacity within management approaches. A shift toward more integrated decision frameworks will improve sustainable outcomes for future water reuse practices throughout Arizona.

INTRODUCTION

Much of the western United States suffers from a scarcity in natural water supplies. Yet it is the part of the country that has experienced the greatest population growth over the past half century. In the 1990s, western states experienced 20% population growth compared to a national average of 13% (Travis, 2007). Nevada, Arizona, Colorado, Utah, and Idaho grew at 37% during that same period (Getches, 2010). Since 1980, Arizona's population has more than doubled, increasing from approximately 2.7 million to over 6.3 million residents by 2006 (Gober and Jones, 2007). Today, Arizona remains one of the fastest growing states in the country, with population growth primarily concentrated in urban areas. The state population is projected to grow to almost 13 million by 2050, with more than 60 percent of that growth predicted by 2020 (USEPA, 2007). These patterns underscore the need to identify more sustainable approaches to water management in Arizona (Eden and Megdal, 2005).

As municipal growth increases and freshwater demands continue to intensify and strain existing water supplies, water resources policy and management are topics that increase in both complexity and consequence. Historic management of rivers has been aimed at creating or maintaining water supplies through engineering and political lenses focused on ensuring reliable water supplies, limiting flood damage, and reducing pollution (Karr & Chu, 2000).

One consequence has been the modification of watercourses, with more than ninety percent of riparian areas altered or degraded in the western United States (Gibbs, 2000; Patten, 2006). While these strategies have been deemed successful in the past, the critical discourse of sustainability questions how much these approaches should be continued (Gleick, 2010).

Realizations that riparian and wetland ecosystems provide many beneficial services have shifted thinking in science and policy circles toward more “socioecological” (or “socionatural”) frameworks (Medema *et al*., 2008). Through this framing, complexity, variation, and uncertainty are accepted as inherent properties of linked social and natural processes (Gunderson and Holling, 2001; Naiman *et al*., 2005; Brauman *et al*., 2007). In response, a number of management frameworks (e.g., adaptive management, integrated water resources management) have emerged in the last thirty years. These frameworks have been organized to serve as testable premises, or prescriptions, designed for knowledge production and feedback loops to achieve specified desirable outcomes and manage uncertainty (Medema *et a*l., 2008). However, integration of these frameworks into practice has proved difficult to achieve.

Nowhere is this conflict more apparent than in the arid and semi-arid southwestern United States, a region with growing populations and limited water supplies highly dependent upon annual variability. During the twentieth century, the development of dams, storage reservoirs, delivery infrastructure, and improvements in groundwater withdrawal added to the reliability of water supplies and encouraged population growth (BRP, 2010). Freshwater consumption for urban and agricultural practices has led to significant declines in groundwater levels and the loss of approximately 35% of perennial surface flows in Arizona

(Turner and Richter, 2011). Paradoxically, rapid urbanization has also led to the production of large volumes of municipal wastewater often discharged into nearby channels propagating the development of effluent-dominated riparian ecosystems (Tellman, 1992).

Despite progress in recognizing the need for sustainable water supplies, water policy and management in Arizona remain fundamentally driven by uncertainty over water scarcity, calling for alternative water supply and water reuse options. Consequently, policy makers and resource managers face a new challenge: create distribution systems that balance water for human consumption with environmental needs. Decision makers must determine how and how much to change management frameworks and water development strategies to meet the goals of sustainability. There are several ways in which they may do so. One approach is by integrating ecological information into decision frameworks with the overall goal of linking release, recharge, and overall renewability of water supply. A second way is by more deliberately engaging and reconciling the value of water used for human development and water for the environment. For example, there is value in releasing water as environmental flows, as well as reusing it to support direct human uses. These uses are in increasing opposition to each other as policy makers look to increase water supply, and managers need ways to consider and balance economic value of ecosystem services. A third method is using an integrated water resource management (IWRM) approach that encourages more reflexive, adaptive styles of decision making, which leading thinkers suggest are needed to manage critical resources in the 21st century (Holling, 1973; Gunderson and Holling, 2001; Medema *et al*., 2008).

Although water policy has many dimensions, in this paper we focus specifically on treated wastewater (effluent). The goal of this work is use current science to inform policy regarding the use of effluent for environmental flows. In the first part of the chapter we examined the history of water policy driving the management and release of effluent. Next, we explored spatial patterns of effluent release in the Arizona landscape. Finally, we devised recommendations for a more integrated water resources management approach. Ultimately this work will inform decision frameworks for policy makers and managers regarding the release of effluent to maintain or restore riparian ecosystems.

Part 1. Arizona water policy: reframing of effluent as a resource

As a result of a long and complicated legal history, Arizona water policy differentiates water resources into four categories: surface water, groundwater, Colorado River water, and effluent. Each is managed through different systems, under different agencies, and subject to various levels of regulation. Water quality is managed separately from water supply, with the federal government generally governing water quality and state laws governing water rights and quantity management. Additionally, each water resource is considered a discrete entity, without continuity or interconnections in the hydrological cycle, further obscuring the advancement of integrated management and sustainability.

For the past few decades, Arizona has largely managed to meet its water demands through groundwater overdraft, supplemental surface water supplies from the Colorado River and local rivers, and limited water reuse. Arizona water law is governed by the prior appropriation doctrine, which can generally be summed up as “finders-keepers,” giving superior water rights to those who first diverted surface water over those who later attempted to divert it (Gillian and

Brown, 1997). Under this doctrine, the State has traditionally been able to adapt and evolve to changing user needs and fluctuations in surface and groundwater supplies (Jacobs & Holway, 2004). However, as uncertainty over water scarcity intensifies, maintaining current water supplies is growing increasingly challenging and demands for alternative water supplies are mounting.

An important moment in the history of Arizona water law occurred in the early 1930s with the Arizona Supreme Court decision in the *Southwest Cotton* case, which established the beneficial use doctrine. The decision had severe consequences on groundwater levels in Arizona - it allowed overlying landowners to pump groundwater from below if the water was put towards a "beneficial use," which went largely undefined and unregulated (Gelt, 2008). During the following decades, technological advancements improved groundwater pumping efficiency, bringing large amounts of groundwater to the surface and resulting in extreme levels of depletion and loss of surface flows (Evans, 2008). The need for regulated management and control grew, but did not truly appear until the 1980s, with the Groundwater Management Act of 1980 (Act) (Pearce, 2007).

The Act established a timeline for reduction and elimination of groundwater pumping in certain areas of the state by creating active management areas (AMAs) and irrigation non-expansion areas (INAs) (August & Gammage, 2007). This also led to the formation of the Arizona Department of Water Resources (ADWR), which is charged with overseeing the State's water resources, managing the AMAs and INAs, and achieving long-term dependable water supplies (ADWR, 2009a). However ADWR's administrative authority to quantify and limit groundwater use extends only to the groundwater basins under the AMAs, which comprise a small portion of the State's land area but most of its population (Jacobs and Holway, 2004).

The 1989 Arizona Supreme Court decision (*Arizona Public Service Co. v. Long*) had significant impacts on the generation and fate of effluent. This ruling identified effluent as water rather than some novel substance, but it did not retain the 'character' of the waters that compose it (groundwater and surface water in varying ratios) (Evans, 2008). Effluent was also established as the property of the entity that treated the water, since it is no longer of the same character as surface water. From this outcome, treatment facilities are not obligated to discharge their effluent for the appropriation of downstream users – it can be put to any reasonable use they see fit. If a treatment facility discharges its effluent to a stream in an effort to dispose of it, the water becomes 'surface water' once again, and is subject to appropriation like any other surface water in the State (*Arizona Public Service, Co. v. Long*, 1989). The facility may also use a natural channel for conveyance to a designated downstream user – they are not required to use a piping system. The Arizona legislature retains legislative and regulatory control over the use of effluent, though it is currently only restricted by its reuse application type based on its treatment quality (by the Arizona Department of Environmental Quality [ADEQ] and the U.S. Environmental Protection Agency [EPA]) and is not subject to regulation by ADWR (Woodard & Jacobs, 1990). The *Arizona Public Service, Co. v. Long* (1989) case "enabled the formation of a market in effluent for which the legal and institutional barriers are relatively low" (Eden et al., 2008).

One of the main failures resulting from the Act is a lack of recognition of the interdependence of surface and groundwater resources. An unintended effect of this vast legislation that focuses extensively on groundwater rights, but largely ignores surface water rights, has been an increase in the importation and depletion of surface water supplies, mostly from streams (Evans, 2008). Thus, the separate water law schemes for groundwater, surface water and effluent represent one historical barrier to managing the resources conjunctively. ADWR has little authority to limit surface-water users or any legal control over reclaimed water (Glennon, 2007). Despite the fact that further restrictions were placed on groundwater use with the passage of the Act, some prior uses were grandfathered in -new irrigation is prohibited for groundwater users in the AMAs, and all new developments must show a 100-year'Assured Water Supply' to prove the availability of a renewable water supply (Glennon, 2007). This piecemeal management makes it difficult to plan for sustainable water resource management, as already witnessed by the predicted difficulty in attaining groundwater 'safe yield' in the AMA by 2025. In addition, the legal system in Arizona does not recognize environmental instream flows as a 'beneficial use' of water, leaving the environment almost completely out of the equation for water resource managers as they consider how to balance all demands with a limited supply (MacDonnell, 2009).

Policy fragmentation: consequences for effluent release. Water quality laws at both the federal and state levels are simply designed to assure that if there is water in a stream, the quality of that water will be protected. Additionally, water quality regulations have become increasingly rigid, sometimes resulting in less water released into a waterway. While Arizona's state law emphasizes protecting groundwater from contamination there is nothing in these laws to require that flows remain in the channel. The *Long* decision made it very difficult for ADWR to regulate the use of effluent. It also made it difficult for treatment plant operators to negotiate contracts with downstream users since once effluent is discharged into a watercourse it becomes appropriable as surface water. This means that a discharger who desires to maintain downstream flow to benefit a riparian area cannot be sure that the water will remain in the channel after discharge because it can be appropriated by a downstream user and removed from the waterway. Finally, there is no law designed to protect streams as a whole from both the water quality and water supply perspectives, nor does any agency have this responsibility (Tellman, 1992).

Part 2: Spatial patterns of effluent-dominated waterways

Introduction. The need for spatial information and reliable data on the quantity and location of available treated wastewater has become an increasingly important part of developing a more integrated water management approach (ADWR, 2010a). While dischargers have been required to provide monthly data reports as part of their permitting process, those data have not been monitored or maintained on a statewide level (ADWR, 2010a). Because of this, there is some uncertainty as to the exact amounts and locations of treated wastewater generated across the state. Further, there is no compiled information on the types of stream channels (or other locations) into which the effluent was discharged, an issue of importance given that the long-term ecological outcomes of releasing effluent into intermittent vs. ephemeral river channels may be quite different. Additionally, there has not been a comprehensive assessment of viable reuse options for each point of effluent generation (Fox, 2010). During the writing of the State Water Atlas, there were attempts to collect and quantify these data (ADWR, 2010b), however integrating the data from a variety of sources with variable consistency in data management has been challenging (Rock et al., 2009). The objectives of this section are to assess spatial and temporal patterns in treated wastewater generation and effluent-dominated waterways across the state, quantify variability in riparian response given physical conditions (i.e., depth to groundwater, geology) and use these data to inform a decision framework for maintenance and restoration of riparian habitat.

Methods. To identify patterns in treated wastewater generated throughout the state, we obtained data using permit data from the Arizona Department of Environmental Quality (ADEQ). First, we identified facilities under the Arizona Pollutant Discharge Elimination System (AZPDES) Permit Program, which is required of all facilities discharging pollutants from any point source into waters of the United States (navigable waters). Pollutants can enter waters of the United States from a variety of pathways, including agricultural, domestic and industrial sources (ADEQ, 2004). We then corroborated those data with Aquifer Protection Permits (APP) which are required if you own or operate a facility that discharges a pollutant either directly to an aquifer or to the land surface or the vadose zone (the area between an aquifer and the land surface) in such a manner that there is a reasonable probability that the pollutant will reach an aquifer (ADEQ, 2004). Those two sources allowed us to identify locations legally allowed to discharge, but does not mean those permits were necessarily in use. To increase accuracy even further, we also used Self-Monitoring Report Form (SMRF) data where possible. All facilities with an APP or Reuse Permit are required to submit discharge reports to ADEQ quarterly to demonstrate compliance (ADEQ, 2004). The SMRF data reflects actual quantities of treated wastewater generated on a monthly basis, rather than a simply approved discharge levels. However, it is important to note that there are limitations to these data as a number of data reports were missing for significant periods of time and reporting requirements are not consistent across all facilities, making it difficult to compare information between them. Also, ADEQ's database only extends back in time until the early 1990s, when requirements were established by the EPA and only limiting data are available from the EPA for periods before then.

While these data provide information on discharge locations and volumes, we were interested in obtaining more insight into the facility history, fate of effluent discharge, and environmental conditions. To do so, an interview protocol was designed through a grant from the Arizona Water Institute (Rock *et al.*, 2009) in which treatment plant managers were a series of questions to obtain more historical and environmental insights (n = 48). From these data points we were able to determine depth to groundwater at effluent outfalls and then categorized the existing effluent-dominated waterways into four hydrogeomorphic categories (Table I). Category 1 was defined as perennial (continuous surface flow, shallow groundwater or a confining bedrock layer within 0 – 6 m from the surface). Categories 2 and 3 were intermittent (flow present only during certain periods) and spatially interrupted (perennial stretches with intervening intermittent or ephemeral sections [7 -15 m] for category 2; and intermittent stretches with intervening ephemeral sections [16 – 30 m] for category 3). Category 4 was defined as ephemeral (flowing on in direct response to precipitation, 31+ m; Meinzer, 1923). Finally, we used aerial photography and geographic information systems (GIS) to quantify the extent of riparian habitat downstream of release points for each category.

Results. Arizona has had a long history of effluent generation, and today effluent comprises approximately 3% (or 205, 400 acre-feet) of the water landscape in Arizona (ADWR, 2010). The first wastewater treatment facilities (WWTPs) in the state were constructed in the 1950s near urban centers (Figure 1). In the decades following, the abundance of wastewater treatment facilities quickly grew, with the most significant increases during the 1980s and 1990s (Figure 1). During this period, most of the facilities constructed were smaller dischargers (<5 million gallons per day [MGD]), designed to accommodate expanding suburban development. However, there were also expansions and upgrades to existing WWTPs, contributing significantly to the volumes of effluent generated. For example, City of Phoenix 91st Avenue WWTP, one of the largest WWTPs in the state, expanded from a treatment capacity of 5 MGD in 1958, to 45 MGD in 1965, and reached its current capacity of over 180 MGD in the 1990s (City of Phoenix, 2008; Figure 2).

As the number of WWTPs and treatment volumes expanded, increasing volumes of effluent were discharged into nearby channels bolstering the development of effluent-dominated waterways. Currently, the Arizona Department of Environmental Quality has identified and legally characterized thirty-eight waterways as dependent upon effluent waters (Figure 3; Arizona Administrative Code, R18-11-113). However, the number of waterways receiving effluent is much higher, though not legally designated as effluent-dominated and are found in a variety of settings throughout the state and comprise approximately 91 miles (146 km) of flow (Rock et al., 2009; Appendix I).

Based on a sample of 33 treatment facilities we found that the treated wastewater generated has a number of different end uses ranging from municipal and agricultural reuse to release into waterways (Figure 4). We found that approximately 45% of the treated wastewater generated from these facilities is discharged into waterways and another 3% into waterbodies (Figure 4). Of the volume of treated wastewater released into channels, approximately 45% discharge into category 4 (ephemeral), 25% into category 3 (intermittent, interrupted), nearly 20% into category 2 (perennial, interrupted) interrupted, deep waterways, and approximately 10% into category 1(perennial; Figure 5A).

Because the long-term ecological outcomes of releasing effluent into intermittent and ephemeral river channels are not well understood, questions remain regarding how surface and groundwater interactions influence the spatial extent and development of riparian ecosystems receiving effluent. Aerial photo analysis revealed that riparian vegetation response in terms of vegetated river kilometers and hectares of forest differs strongly depending on the type of waterway into which treated wastewater is discharged. In perennial systems nearly 24 hectares of habitat is maintained by the release of 1 million gallons per day (MGD) while in ephemeral systems 1.2 hectares of riparian habitat is supported by 1 MGD of treated wastewater (Figure 5B). Figures 6, 7, 8, and 9 provide examples of treatment facilities releasing effluent in each hydrogeomorphic setting and highlight the downstream area of riparian vegetation supported in each system. Habitat response also varies based on the interaction of discharge volume and hydrogeomorphic setting. Habitat response in perennial systems is high even with lower amount of effluent release, although it is more difficult in these systems to identify how much the effluent subsidizes flow and downstream vegetation Figure 10A). When looking more closely at systems with less than 20 MGD release, patterns emerge revealing that effluent subsidy results in greater riparian response in systems with more shallow groundwater tables (Figure 10B).

Part 3: Opportunities and challenges for securing effluent for environmental flows.

Until recently, effluent was considered a ‘nuisance commodity’ to be disposed of as cheaply as possible (Pearce, 2007). This perception led to the disposal of wastewater into nearby channels, and the emergence of effluent-dominated waterways in Arizona. Today, views of treated wastewater have begun to shift from effluent as a little-appreciated and under-utilized resource to an increasingly valuable water source in sustainable management frameworks (Chapman, 2005). With stricter water quality standards, improvements in treatment technology, and growing municipal and agricultural demands for freshwater, wastewater reuse continues to emerge as a vital component of sustainable water supply and demand management (Levine & Asano, 2004). However, existing water policy and management in Arizona lacks the adaptive capacity to allow decision makers to consider the dynamic relationships among water consumption, effluent generation and release, riparian ecosystems, and overall reuse goals.

In this last section, we explore opportunities to secure effluent for environmental flows, using scientific evidence from the spatial analysis, field data and greenhouse studies to inform decision processes. Assuming that riparian ecosystem maintenance and restoration are goals of a more sustainable water management framework, best practices for effluent release need to be developed as part of an integrated approach. The recommendations are designed to provide ideas for preserving and restoring riparian habitat within a landscape of water reuse and sustainability. Reforming water management and policy will have to occur across multiple levels of government – local, regional, state, federal – and will require integration across those levels. We have devised some recommendations and ideas for changing the rules to secure effluent for environmental flows, but we do not discuss potential trade-offs within these changes.

Recommendation #1 - Development of criteria specific to effluent-dominated waterways

Under Arizona State law, “water of the state” means “all waters within the jurisdiction of this state including all perennial or intermittent streams, lakes, ponds, impounding reservoirs, marshes, watercourses, waterways, wells, aquifers, springs, irrigation systems, drainage systems and other bodies or accumulations of surface, underground, natural, artificial, public or private water situated wholly or partly in or bordering on the state” (A.R.S. § 49-201.40). Because water is regulated through a patchwork of laws and doctrines, the United States has a history of using the courts, rather than legislative bodies, to apply overarching laws to specific cases. As such, default environmental protection has been provided to Arizona’s water bodies through the application of federal laws that do not account well for regional climate and water differences (Leshy, 2009).

The basis for permit determinations has historically been through the development of criteria documents, often applied through a one-size-fits-all approach. What this means is that water quality standards for ephemeral watercourses have been the same as those applied to large rivers. While there have been improvements in recognizing climatic and hydrologic variation by regions (Omernik *et al.*, 2011), effluent-dominated systems and of effluent-dominated their unique characteristics have not been recognized or incorporated into existing policy frameworks. Studies on ephemeral and intermittent systems that highlight their contribution to biological diversity and how they fundamentally differ from perennial systems have informed resource management in water-limited regions(Stromberg *et al.*, 2008, Katz *et al.*, 2009). Similar studies are needed for waterways driven by urban water sources, such as effluent.

Recommendation #2 - Establish legal relationships between ground and surface water that includes effluent.

Arizona has been gradually taking steps towards implementing the features of a conjunctive management system. For example, the establishment of the Central Arizona Water Conservation District and Arizona Water Banking Authority has been successful in accumulating significant water storage credits and off setting groundwater withdrawals (Feller, 2007). This has been an important step Arizona has taken in implementing features of a conjunctive management system (Evans, 2008). However, skeptics still see these measures as temporary, and argue that riparian areas remain at the forefront of environmental concerns associated with excessive groundwater pumping and failed water management policies that have resulted in lowered river and surface water levels.

If Arizona continues to recognize the need to change its long-standing loyalty to the bifurcated system of water law, legal recognition of the interdependencies and interconnectedness of ground and surface water, including specific management for effluent, needs to occur. This would provide a progressive step toward integrated management in which comprehensive legislation that includes effluent for environmental flows could be developed. This type of management would have to be adaptive across multiple levels of government to address geographic differences on area and specific needs.

Recommendation #3 - Refine the instream flow permitting process with specific guidelines for effluent release and environmental flows.

Arizona water law has provisions for appropriating water for wildlife, fish, and recreation. ADWR implements these provisions through an instream flow permit, a special type of permit to appropriate surface water and leave it in the stream at a particular location for those end uses (wildlife habitat, recreation) (ADWR, 2004). However, the instream flow program has developed through interpretation of statutes, and does not have a specific legislative mandate. Because effluent is available and an increasing source of water, an instream flow permit would seem the ideal way to preserve riparian habitat adjacent to an effluent-dominated waterways. Specifically, all a downstream user would have to do is file for an instream flow permit to specifically maintain effluent discharge. The process, however, is not that straightforward. Under the appropriation doctrine, instream flow rights are junior to existing rights which means that a permittee is given rights to water through the instream flow permit only as long as it's discharged. Thus, a discharger could, at any time, decide not to release the water.

Strengthening the value of instream flow permits for the preservation of habitat along effluent-dominated waterways offers the opportunity for increased coordination between local, regional, and state governments. The program would have to be administered at the state level, but local ecological knowledge and regional data can help guide decision processes. Scientific research can help to inform where instream flows may provide the most habitat and economic values. Thus, if a discharger chooses to cooperate with a downstream landowner or agency to maintain habitat, an instream flow permit could protect the flow from the discharge point to the protected area, without another user appropriating the flow in between.

Recommendation #4 - Recognition of riparian vegetation and passive recharge as beneficial use.

In Arizona, current state-recognized beneficial uses include domestic, municipal, irrigation, stockwatering, power, mining, recreation, wildlife and fish, and groundwater recharge (ADWR, 2010). Riparian habitat is not currently included as beneficial use, although it is highly valued and public concern is high regarding the impact that limited water will have on *Populus-Salix* (cottonwood-willow) forests (Bush et al., 2006). If laws were amended to include “riparian vegetation” as a beneficial use, the applicability of instream flow permits would be strengthened. Science can help inform this decision process. The differential responses of downstream riparian vegetation in different hydrogeomorphic settings reveals that there may be locations better suited to maximize riparian response.

In tandem with recognition of riparian vegetation as “beneficial,” the value of passive recharge needs to be more significantly recognized, including the amount of credits given for releasing water into channels. There are three principle means of conducting recharge are (1) constructing facilities such as recharge basins or ponds that allow water to soak into the ground (direct recharge), (2) allowing water to run down existing stream channels and infiltrate (passive recharge), (3) paying a farmer to reduce groundwater pumping by accepting an alternative water supply, generating “credits” to pump the saved groundwater in the future (in lieu recharge) (Baker, 2009). Currently, focused recharge is being prioritized in Arizona as the method to offset municipal freshwater demands and augment water supply (Lohse *et al*., 2010). The law regarding the status of treated wastewater could be amended to prioritize passive recharge credit for effluent discharged for environmental flows. Such change could also prevent anyone else from appropriating that water and would consider recharge within the stream as beneficial use, subject to the same rules as beneficial uses. Scientific information could further inform this process by identifying waterways with more ideal environmental conditions in which riparian response would be maximized.

Recommendation #5 - Build adaptive capacity and design integrated approaches for effluent release and riparian ecosystem development

Building sustainable urban water systems requires designing them to adapt to changing conditions and needs (Holway, 2009). With increased recognition that traditional patterns of water development have taken a heavy toll on freshwater ecosystems, much more attention is being given to securing water for the environment (environmental flows) (Poff *et al*., 2010). Many state laws provide a number of ways to ensure environmental flows, including putting flow-protecting conditions on water use permits and approvals of water transfers, but these tools tend to be used sporadically. To maximize riparian habitat preservation and restoration potential, Arizona needs to design effective, comprehensive programs to secure flows for riparian habitat preservation and recovery. This research has shown that hydrogeomorphic conditions, volume of discharge, and quality of treated wastewater impact the outcome of riparian vegetation response. Ecological conditions for the river setting should be determined and should also include societal values, which can be accomplished through stakeholder participation to establish ecological and cultural values to be protected or restored through river management

Few states have programs that aim for systematic and comprehensive protection of ecologically based flows. Moreover, when such tools do exist, they often focus narrowly on protecting aquatic wildlife, even though this may not be a good proxy for general ecological health (Leshy, 2009). Building sustainable urban water systems requires designing them to adapt to changing conditions. As freshwater demands continue in the water-limited Arizona landscape, both the policy frameworks and the institutions overseeing decision processes must be able to evolve and adapt, identify clear goals and outcomes, and establish thresholds to trigger feedback and adaptive capacity within water management. Good data on historic and current conditions, coupled with future projections, are a fundamental prerequisite for identifying thresholds and integrating scientific information into water management (Holway, 2009). Scientific research can help inform best management practices and increase adaptive capacity for water reuse planning, prioritizing effluent release for riparian habitat preservation and restoration.

CONCLUSIONS

In water-limited regions, increasing municipal freshwater consumption raises the need for, and attractiveness of, reclaiming treated wastewater and using the resulting effluent to meet a range of growth-driven water demands. As human uses for water continue to outweigh the values of flowing streams and riparian habitat, questions remain about where the environment, and more specifically riparian restoration, fits in. Technological advances and engineering solutions have advanced urbanization in the modern landscape, but not without the alteration or loss of perennial surface flows. The riparian areas that still exist (whether perennial, ephemeral, or intermittent) remain extremely important for supporting biodiversity in a semi-arid landscape. Today, many rivers - Santa Cruz River downstream of Nogales and Tucson, the Salt River downstream of Phoenix, and Rio de Flag in Flagstaff – maintain perennial flows due to effluent subsidy. Yet little is known or understood, both ecologically and from a policy perspective, about effluent-dominated waterways. This research has shown that the composition and amount of habitat are drastically different along effluent-dominated systems in varying hydrogeomorphic settings. Appropriate decision rules that utilize scientific information are needed to inform future sustainable water resources management approaches. However, current water resources management is governed by an intricate, three-dimensional mosaic of laws that have accreted in layers at both the federal and state levels resulting in an inert system that does not readily admit change (Leshy, 2009). It is growing increasingly more urgent to integrate scientific data in the advancement of an adaptive decision framework for the management of wastewater that recognizes the value of riparian ecosystem restoration as an outcome.

Table I. Hydrogeomorphic categories for waterways receiving effluent discharge.

Hydrogeomorphic setting	Depth to groundwater (m)
Perennial river*	0 - 6
Interrupted perennial, deep water table	7 - 15
Interrupted intermittent, very deep water table	16 - 30
Ephemeral channel	31+

**also includes systems with bedrock (confining layer) 0 - 6 m.*

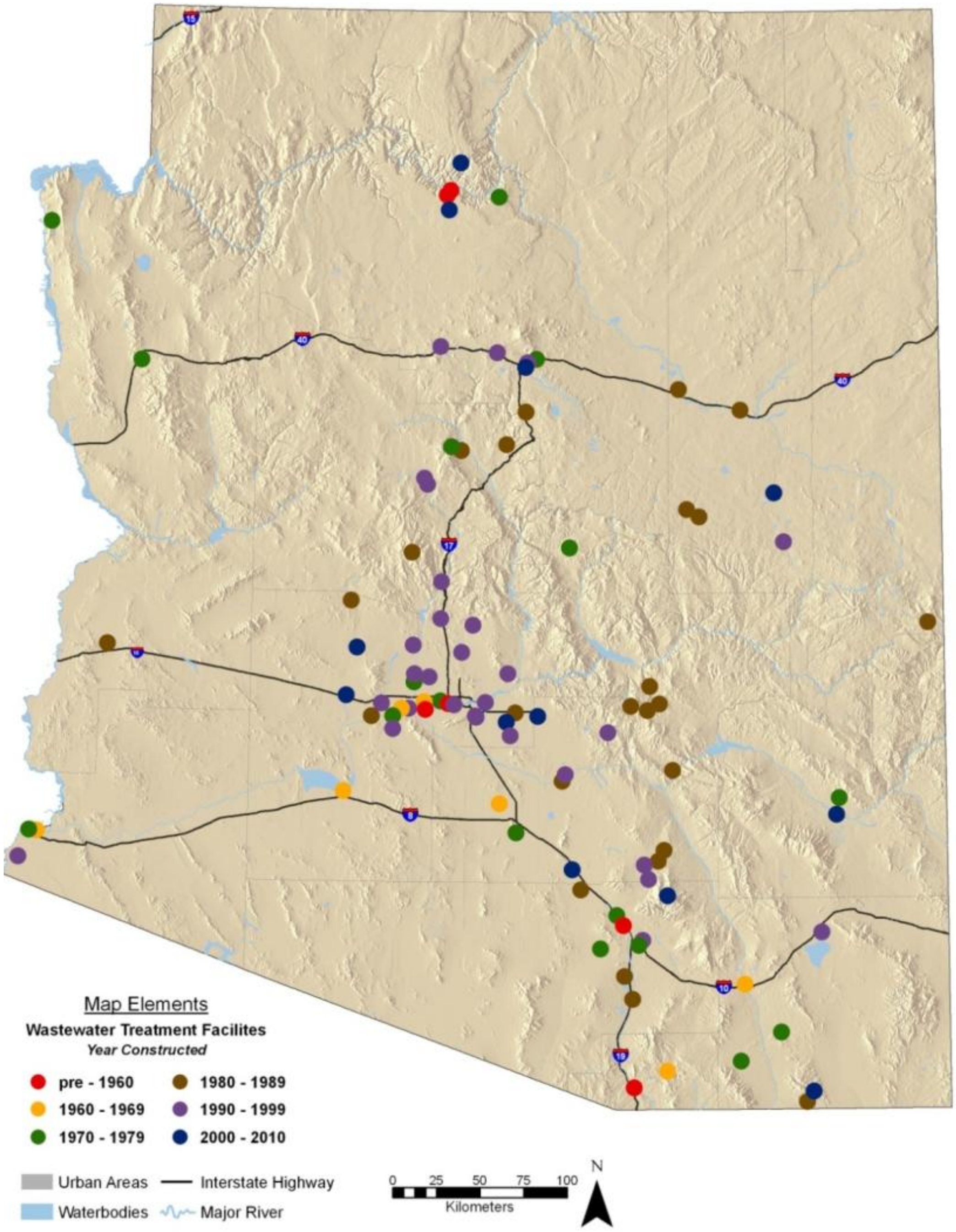


Figure 1. Spatial and temporal patterns in the development of wastewater treatment facilities in Arizona since the 1950s.

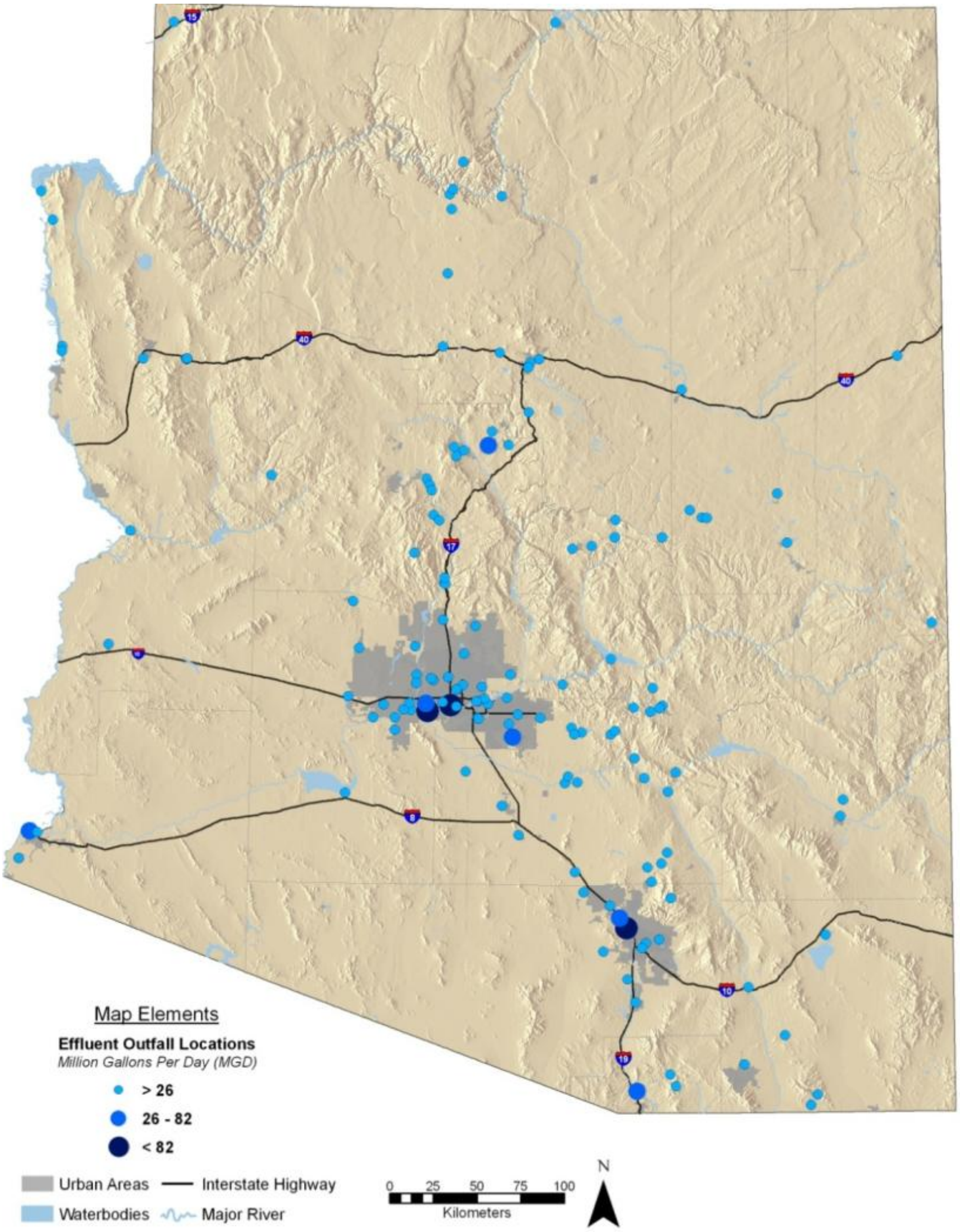


Figure 2. Permitted effluent outfall locations and discharge volumes throughout the state of Arizona. *does not indicate effluent is currently being discharged. (Rock *et al.,* 2009)

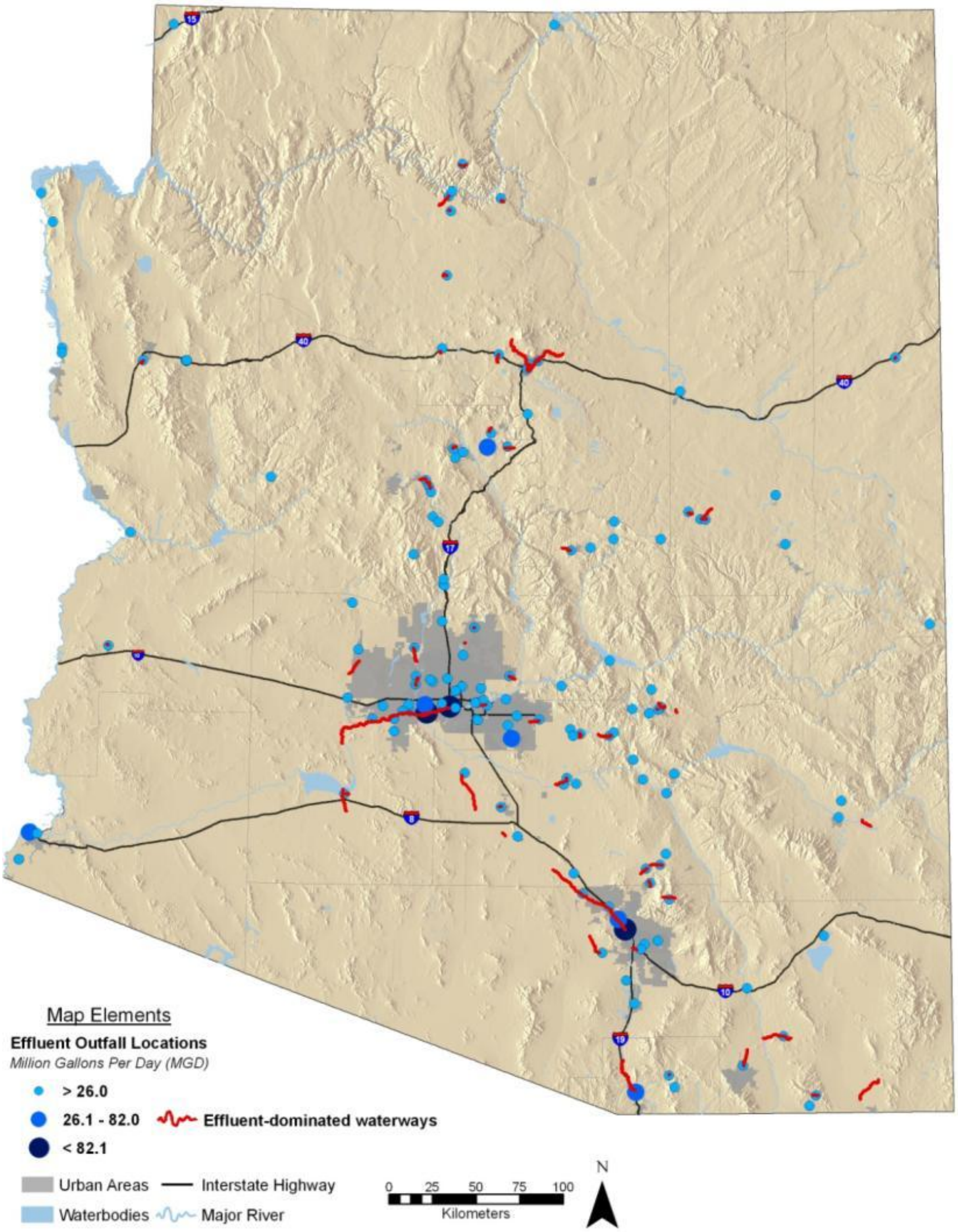


Figure 3. Permitted effluent outfall locations and volumes with downstream effluent-dominated waterways in Arizona (Arizona Administrative Code, R18-11-113) (Rock *et al.,* 2009)

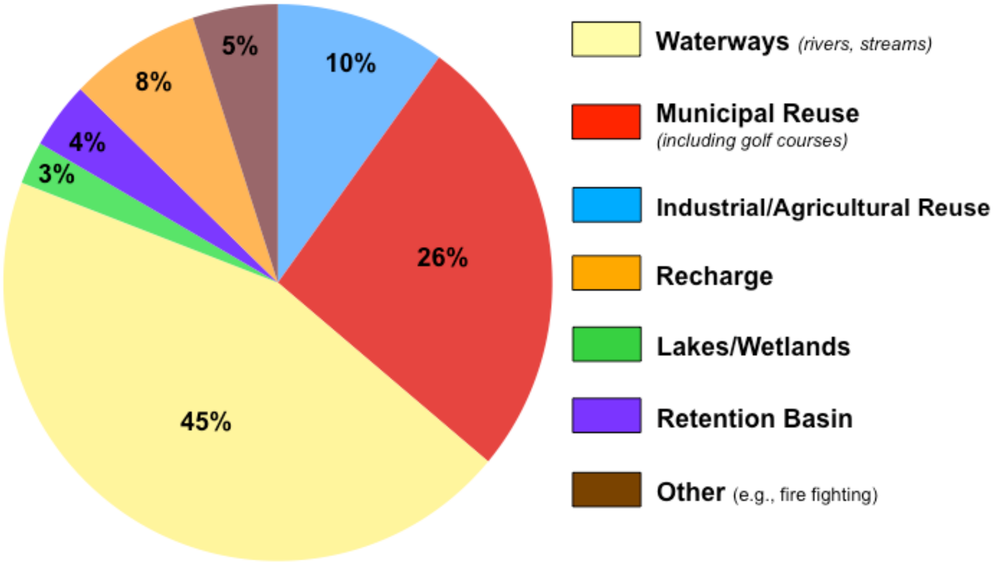


Figure 4. Fates of generated effluent in the modern landscape. Based on sample of 42 treatment facilities

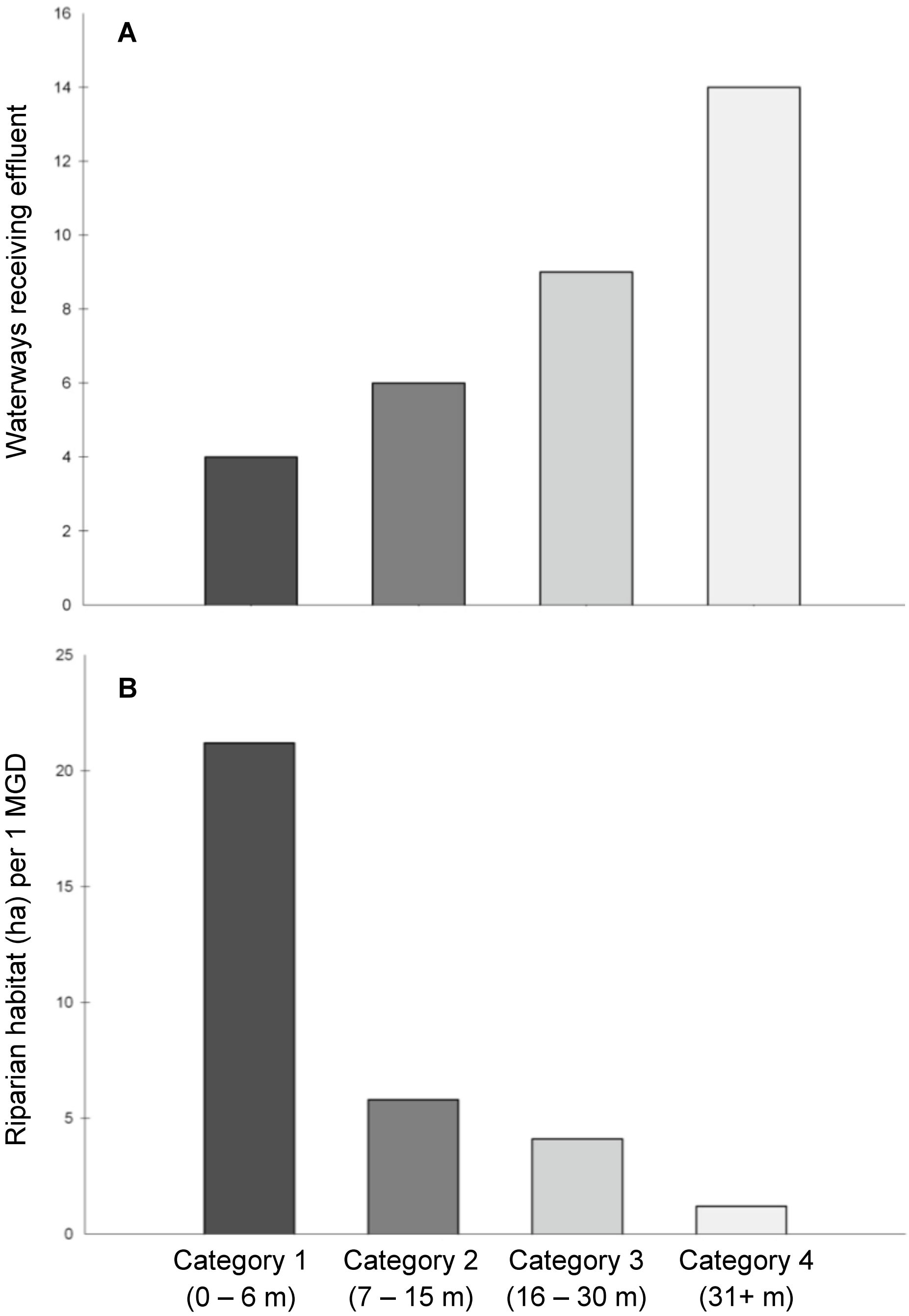


Figure 5. (A) Number of waterways receiving effluent by hydrogeomorphic category, (n = 33). Category 1 = perennial; Category 2 = perennial interrupted; Category 3 = intermittent interrupted; Category 4 = ephemeral. (B) Riparian habitat by hydrogeomorphic setting. Areas are normalized by volume of discharge to represent hectares per 1 MGD.

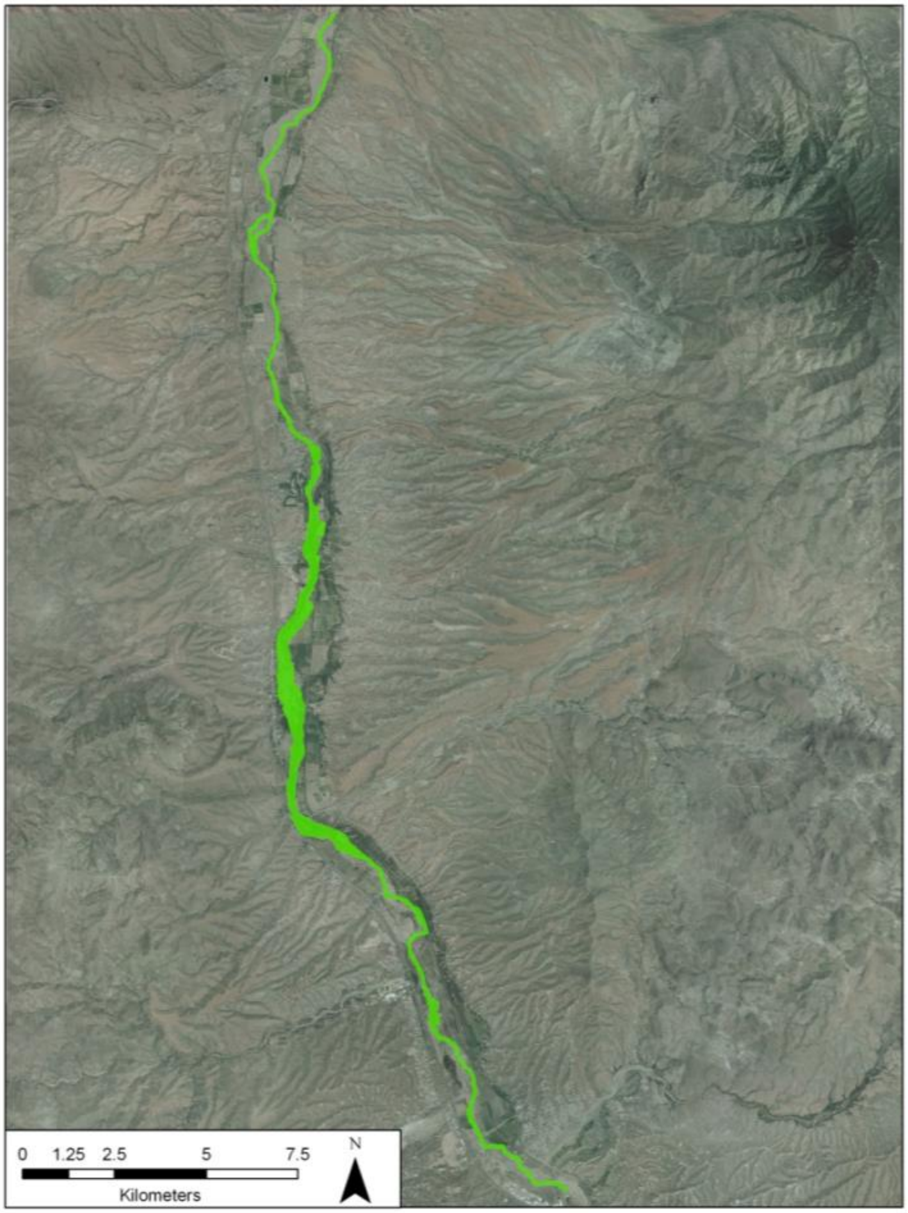


Figure 6. Extent of riparian habitat supported downstream in a category 1 (perennial) setting (0-6 m). The representative site is downstream of Nogales International Wastewater Treatment Facility. 17 MGD of effluent supports 480 hectares of riparian habitat over 45 kilometers in length.

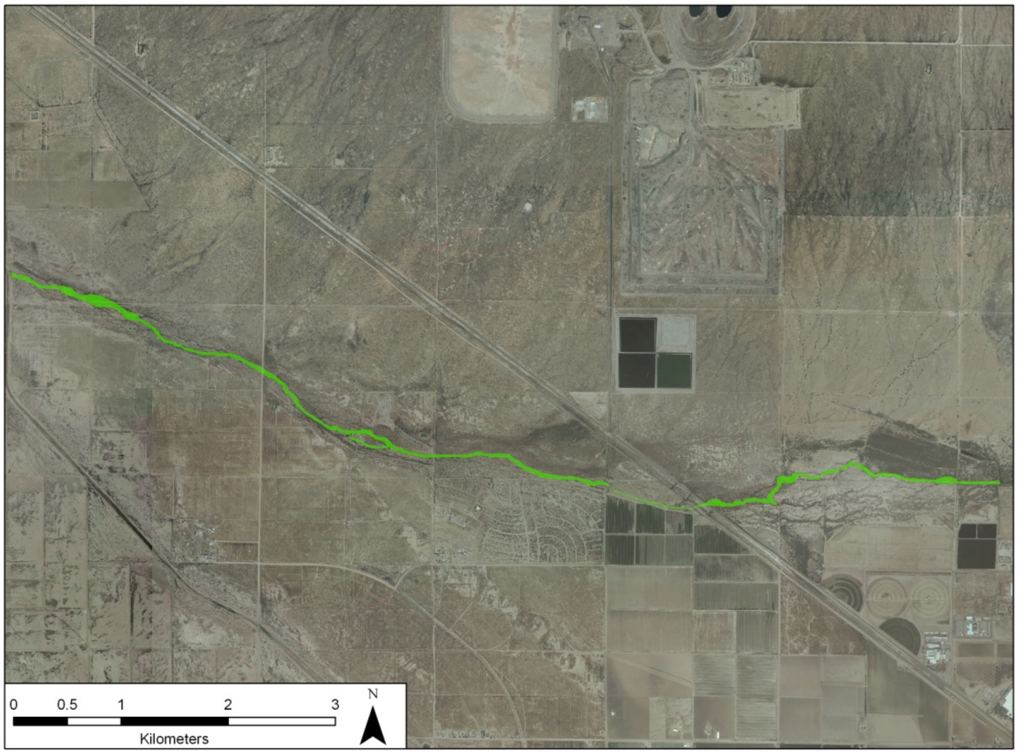


Figure 7. Extent of riparian habitat downstream of a category 2 river (perennial, interrupted with deep groundwater [7 -15 m]). The site is downstream of Casa Grande Wastewater Treatment Facility. 6 MGD of effluent supports 35 ha of riparian habitat over 9 kilometers in length.

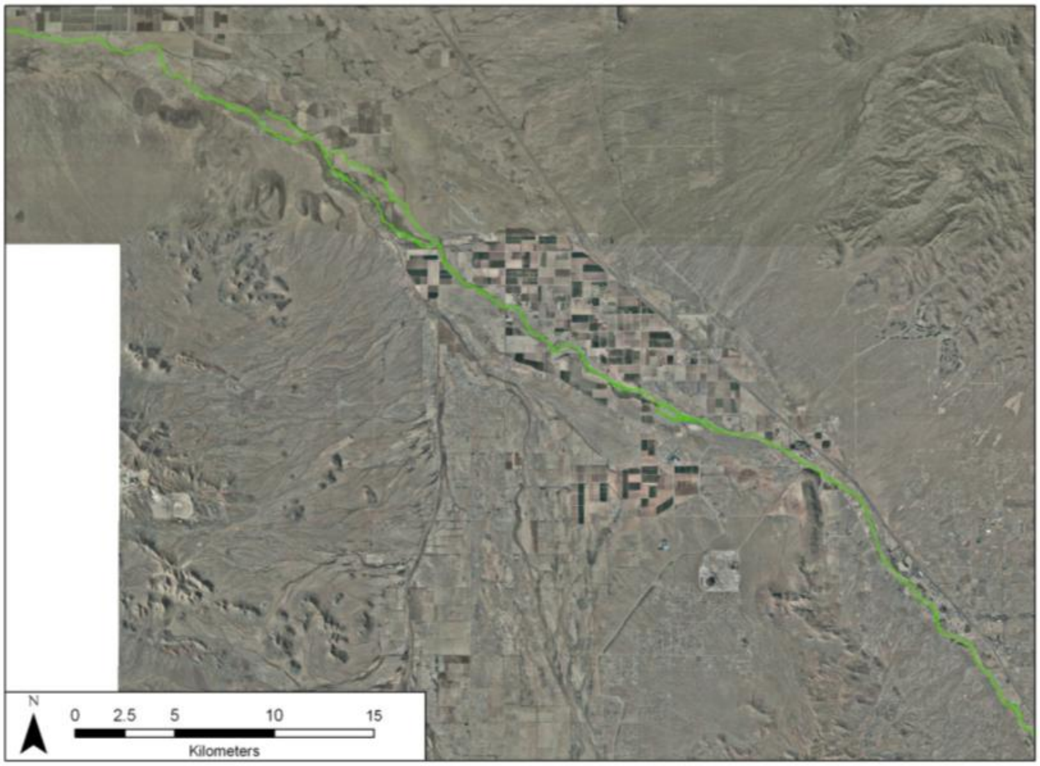


Figure 8. Extent of riparian habitat downstream of a category 3 river (intermittent, interrupted with very deep groundwater [16 - 30 m]). The site is downstream Roger and Ina Roads Treatment Facilities. Approximately 78 MGD of effluent supports 340 ha of riparian habitat over 65 kilometers.

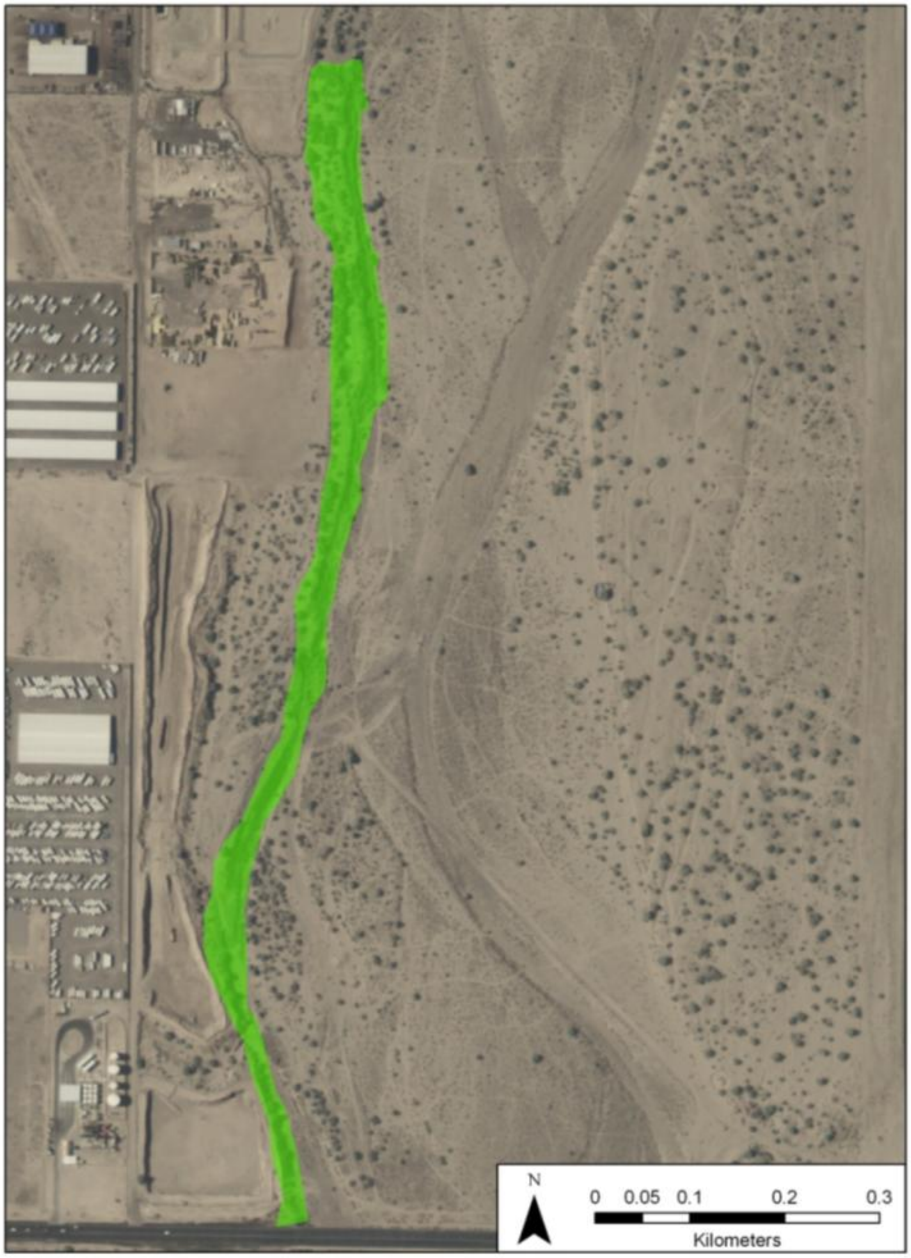


Figure 9. Extent of riparian habitat downstream of a category 4 river (ephemeral channel with deep groundwater [31+ m]). The site is downstream of El Mirage Wastewater Treatment Facility. 4 MGD of effluent supports 4.8 ha of riparian habitat over 1.3 kilometers.

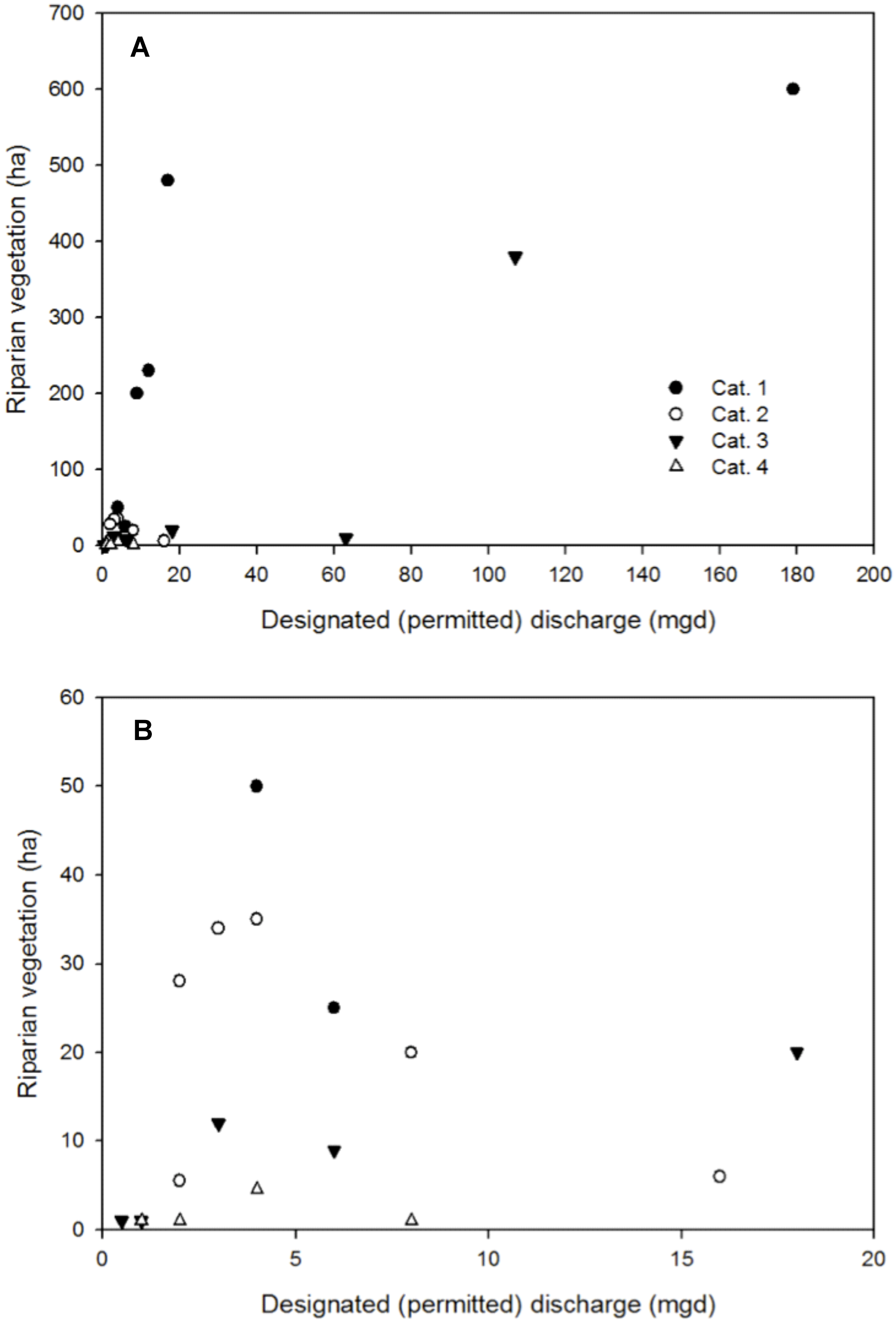


Figure 10. Discharge volumes and riparian habitat area (ha) supported (A) from all sampled WWTPs (n = 33); (B) Riparian habitat area supported by discharge volumes < 20 MGD.

3. NUTRIENTS AND NITROPHILES: EFFECTS OF TREATED WASTEWATER ON DRYLAND RIPARIAN PLANT COMMUNITIES

ABSTRACT

During the twentieth century, nutrient inputs to aquatic and riparian ecosystems worldwide increased dramatically leading to changes in community composition and ecosystem function. For riparian ecosystems of the southwestern United States, declines in surface water flows coupled with the release of treated municipal wastewater have resulted in the emergence of effluent-dominated waterways. However, little is known about the riparian plant communities that are created and sustained by treated wastewater. I conducted a greenhouse experiment and gathered field data to determine how elevated nutrient levels in treated municipal wastewater influence riparian plant community response in three different hydrologic settings. Plants from soil seed banks collected from ephemeral, perennial, and effluent-dominated rivers were monitored in a greenhouse to address how varying concentrations of nitrogen and phosphorus would influence richness, biomass, density and composition. Streamside herbaceous vegetation was sampled for two years at twelve sites along the effluent-dominated Santa Cruz River and at nine sites along the San Pedro River, our control. I used a modified Ellenberg index to further assess composition and found that effluent-dominated systems had greater abundance of nitrophilic species, those with higher nitrogen affinity, such as *Conium maculatum* and *Polygonum lapathifolium*, in both the experiment and field settings. In all settings, biomass and plant height increased while stem density and richness decreased with increasing nutrient concentrations. Hydrologic setting is also an important factor on community response, as biomass and

density were significantly higher in the perennial and effluent-dominated seed banks. As anthropogenic nitrogen inputs currently equal or exceed natural N inputs in many ecosystems and as larger scale restoration is planned for entire landscapes, this study revealed that water quality and hydrologic setting are important ecological variables influencing herbaceous plant community development and population-level processes in waterways receiving treated wastewater.

INTRODUCTION

Nitrogen (N) and phosphorus (P) frequently limit primary productivity across multiple scales, from individual plant growth and reproduction to ecosystem level patterns and processes (Vitousek & Howarth, 1991; Noe *et al*., 2001; Elser *et al*., 2007). Over the last 200 years, human modification to the landscape has significantly increased the amount of nitrogen and phosphorus available to biotic organisms through the production of synthetic fertilizers, land management changes, fossil fuel combustion, and waste management practices (Elser *et al*., 1990; Pasari *et al*., 2010). Elevated inputs of these nutrients have been implicated worldwide in changes in biological diversity and ecosystem services (Smith *et al*., 1999), reflecting the fact that global cycles of N and P have been amplified by c.100% and c. 400%, respectively, by postindustrial human activities, mainly the production of synthetic fertilizers (Falkowski *et al*., 2000; Elser *et al*., 2007).

Riparian ecosystems occupy a unique area in the landscape; as ecotones between aquatic and terrestrial ecosystems, they have a diverse array of biological and physical processes, and a mosaic of vegetation types and structural components due frequent disturbance from floods (Malanson, 1993;

Naiman and Decamps, 1997). Today, nutrient enrichment has been identified as a pervasive disturbance to aquatic and riparian ecosystems, contributing to shifts in community composition and changes to ecosystem function (Boorman and Fuller, 1981; Ostendorp, 1989; Davis *et al*., 1994; Svengsouk and Mitsch, 2000; Verhoeven *et al*., 2006). During the twentieth century, nutrient inputs to river systems worldwide increased dramatically, due primarily to expanding use of fertilizers and treated municipal wastewater discharge (Falkowski, 2000; Tilman *et al*., 2000; Nicola, 2003; ICPDR, 2009). Other important anthropogenic sources of N and P that contribute to nutrient loading in river systems include: deposition of atmospheric N, runoff from animal corrals and feedlots, fertilizer applied to lawns, leaky septic tanks, and the increased abundance of symbiotic N-fixing plants (Verhoeven *et al*., 1996; USEPA, 1999). These trends are predicted to continue with global rates of nitrogen and phosphorus fertilization projected to be 2.5 times and 2.4 times, respectively, that of current levels by 2050 (Tilman *et al*., 2000).

Ecological theory predicts, and empirical studies have shown, that nutrient availability can have strong effects on diversity and species composition of plant communities (Tilman, 1987; Berendse and Elberse, 1990; Morris, 1991; Wisheu *et al*., 1991; Pringle *et al*., 1993; Lamers *et al*., 2001; ICPDR, 2009). Anthropogenic nutrient enrichment has also been linked to plant invasions across ecosystems worldwide (Drake *et al*., 1989; Vitousek *et al*., 1996; Brooks, 2003). While the dynamics of riparian ecosystems and nutrient enrichment in agricultural landscapes in the eastern U.S. and Western Europe have been well studied (Peterjohn and Correll, 1984; Gilliam, 1994; Hill, 1996; Bennett *et al*., 2005), less is known about plant communities that arise from, and are sustained by, nutrient-enriched urban waters, such as treated municipal wastewater. The effects of increased nutrient levels in treated wastewater on plant community composition and diversity may be even more profound in streams arid and semi-arid regions as the availability of soil nutrients, primarily nitrogen and phosphorus, limits plant productivity in North American deserts (Grimm and Fisher, 1986; Schlesinger *et al*., 1996; Fisher *et al*., 2004).

Although the quantity of N and P is important to plant productivity, only certain constituents of N and P are readily available to plants. Response of wetland and riparian plants to nitrogen enrichment will vary according to plant traits, form of nitrogen introduced (ammonia, nitrate, or gaseous NOx), and amount of nutrient deposited (Scherer-Lorenzen *et al.*, 2007). Plants absorb and assimilate both $NO_3^-$and NH_4^+ most readily, and these are the soluble forms of nitrogen found in treated wastewater that move quickly through soils in the shallow groundwater to adjacent river systems (Coffman, 2007). Increases in nitrogen availability can lead to increased productivity, reductions in plant density and diversity, and increases in the size and abundance of high nitrogen, or nitrophilic, species (Pasari *et al.*, 2010). For example, in the Danube River delta, nutrient pollution (including nitrogen, phosphorus and sulfate) has been linked to eutrophication and increases in non-native species (Lamers *et al*., 2001; Pringle *et al*., 1993; ICPDR, 2009).

Plants can uptake phosphorus only when dissolved in water as orthophosphates or polyphosphates, which are the forms in treated wastewater (Shuman, 1994). Phosphorus enrichment can lead to eutrophication and dominance by opportunistic species with high growth rates, short leaf longevity, and root systems with higher ratios of surface area to volume, many of which are non-native species (Schachtman *et al*., 1998; ICPDR, 2009). Required for many metabolic processes, P is absorbed rapidly into plant roots but requires active uptake due to steep concentration gradients between the soil solution and plant roots (Shuman, 1994). Wetland and riparian ecosystems appear to be highly responsive to small changes in P concentrations, leading to dominance by certain species, such as *Typha and Arundo* (Noe *et al*., 2001). Changes in community composition may be perceived as undesirable, particularly if they lead to a shift toward non-native species or a loss of species diversity. In the Florida Everglades phosphorus pollution from agriculture, in part, has resulted in the loss of a plant community tolerant of low phosphorus conditions (Davis, 1991; Chiang *et al*., 2000).

A key question in need of investigation is how nutrient enrichment will affect wetland and riparian ecosystems in arid and semi-arid regions where water is a limiting resource. Rivers in dryland regions exhibit both spatial intermittency, having stretches with perennial and non-perennial flow, and temporal intermittency, with seasonal periods of no flow (Vidal-Abarca *et al.*, 2001; McMahon & Finlayson, 2003; Stromberg *et al*., 2009). These flow dynamics shape diverse ecological processes and maintain distinct aquatic and riparian communities (Brooks *et al*., 2006; Beauchamp *et al*., 2007; Stromberg *et al.,* 2009). Societal demands have also modified the natural variability of flow through surface water diversions, groundwater pumping, and, more recently, the discharge of treated wastewater. Whether water limitation overrides effects of nutrient addition is a question of importance to scientists and decision makers when assessing water resources and riparian ecosystem management. As surface flows have continued to decline and the urban population has continued to increase in the desert southwest, treated wastewater has increasingly been used to supplement and replace base flow, resulting in effluent-dominated streams or ‘‘water bodies [that have] instream flows [that] are entirely dependent on effluent discharges’’ (Brooks *et al.*, 2006). While nitrogen enrichment to riparian ecosystems from agricultural runoff has been extensively studied, much less is known about the effects of long-term release of point source nutrients, such as treated wastewater, on riparian ecosystems in water-limited environments (Adams, 2003).

Hydrogeomorphic setting significantly influences both the extent and composition of riparian habitat that develops downstream of the point of discharge. In Arizona, many of the channels that receive effluent discharge are either ephemeral or intermittent waterways (White, in prep.) These effluent-dominated systems are fundamentally different in water quality and hydrology from the dry or intermittent streams they displace. When treated wastewater is discharged, base flows become perennial, altering temporal and spatial water variability. Further, temperature, dissolved oxygen regimes, nutrient concentrations, and other chemical constituent loadings are altered (Brooks *et al.*, 2006). Concerns that the modified flow regime and increased nutrient loading of treated wastewater alter processes and subsequently change riparian community composition are my impetus for examining effluent dominated systems in semi-arid regions.

The objectives of this study were to determine 1) how riparian plant communities from a dryland region respond to increasing concentrations of nitrogen and phosphorus, and how response differs between nitrogen and phosphorous; and 2) whether riparian plant communities in ephemeral, perennial, and effluent-dominated systems respond differently to the introduction of treated wastewater, using richness, abundance, composition and biomass as community metrics. For objective #1, we expect to see a corresponding decrease in species richness, increase in plant height and biomass, and increase in shoot:root ratios as phosphorus and nitrogen availability increases. We also expect to see a shift in community composition toward nitrophilic species as nitrogen increases. With respect to objective #2, we expect to have higher biomass and abundance in communities emerging from seedbanks obtained from sites with perennial base flows for all treatments, including the non-nutrient control. How riparian plant community composition and productivity may change with increased nutrient availability is important for the management and potential restoration of riparian ecosystems in the southwestern United States

MATERIALS AND METHODS

Experimental Design: Greenhouse Studies

To address our first question, we designed a two-factor controlled greenhouse experiment at Arizona State University to investigate the response of vegetation from riparian soil seed banks to elevated nutrient concentrations (nitrogen and phosphorus). The experiment was conducted from August 15 - December 15, 2008. Air temperature ranged from 19 - 42^{o} C, with an average daytime temperature of 28 ^{o} C. Treatments were arranged as a series of nine stations each receiving nutrient-enriched water to simulate conditions found in effluent-dominated waterways in the southwestern United States. There were three concentrations of nitrogen (low, med, high) and three of phosphorus (low, med, high), resulting in a 3 x 3 factorial design (9 total treatments) (Table I).

To address our second question, we carried out the above experiment for seed banks collected from three hydrological stream types. Each station consisted of nine five-gallon pots (pot dimensions: 22 cm at base, 25 cm at top, 31 cm tall) and included three replicates of riparian seed banks from ephemeral, perennial, and effluent-dominated waterways. Replicates were color coded and randomly arranged within the station. A tenth pot was established in each station to monitor soil moisture and soil pH to eliminate disturbance for seeds and seedlings in the experimental replicates.

Seed bank sources. Seed-containing soil was collected along perennial reaches of the San Pedro River (3 Links Farm, 32° 09' 52" N, 110° 17' 45" W and 32° 10' 48" N, 110° 17' 51" W), effluent-dominated reaches of the Santa Cruz River (Santa Gretudis Lane, 31° 33' 43" N, 111° 02' 45" W and Chavez Siding Road, 31° 38' 45" N, 111° 02' 51" W), and ephemeral reaches of the Hassayampa River (Patton Road 33° 44' 22" N, 112° 41' 38" W and CAP canal 33° 39' 40" N, 112° 42' 00" W) in June 2008. Sites were approximately five kilometers apart. Ninety samples were collected along two 300-meter reaches for a total of 180 samples per river. Each sample was a composite of three sub-samples collected within a two meter wetted zone of the low flow channel to more completely sample the streamside community. The litter layer was removed, and soil was collected to a depth of 2.5 cm using a 5-cm diameter split-core soil sampler. Samples were transported to Arizona State University, mixed to homogenize the seed bank by river type, and stored in a cold room until the experiment was initiated.

Each five-gallon pot was filled with a sterilized sandy loam soil mix 3 centimeters from the top edge. Sampled riparian soils were homogenized by hydrologic setting and spread across the surface of the sterilized substrate to a depth of 2 cm (981.25 cm^3). Gravel was placed in the bottom of each pot to help plug larger drainage holes. Cheesecloth was wrapped around the bottom of each pot to minimize soil loss while still allowing for water drainage.

Watering and Fertilization. Pots were watered using a standard hose-and-bib system and a manifold with nine automatic fertilizer-dispensing systems (EZ-FLO). A timed fertilization system was chosen because it is specifically designed to liquefy highly concentrated, water-soluble fertilizers and proportion them into the water stream. Soils were initially saturated with tap water through a drip irrigation system for a full 24 hours prior to the initiation of the experiment. To maintain soils at or near field capacity and eliminate water stress as a variable, water was delivered via timed drip irrigation for four minutes, twelve times per day using four 0.5 gallon per hour drip emitters per pot. The EZ-FLO technology ensured that the proportion of concentrated nutrients to water remained constant, at a chosen feed rate of 1:500. All delivery concentrations were calculated using that feed rate.

Nutrient concentrations were created using ammonium nitrate (NH_4NO_3) and monosodium phosphate (NaH_2PO_4), both commonly used chemicals in fertilizers. N:P ratios were derived to represent concentrations found in both perennial and effluent-dominated systems (Table II). Nitrogen concentrations were derived from EPA drinking water and treated wastewater standards; phosphorus values were informed by water samples taken from perennial and effluent-dominated waterways. Based on feed rates and gallons of water delivered per day, $NH_4NO_3$and NaH_2PO_4were changed out every twenty days to maintain concentration levels and chemical quality over the sixteen-week period.

All other macro- and micronutrients were assumed to be in the tap water at concentrations sufficient to minimize potential nutrient deficiencies.

Plant Monitoring and Harvest. The experiment was monitored for sixteen weeks, during which time the number and species identity of emerging plants was determined. Some individuals in the seed bank and extant vegetation could only be identified to genus. Plants were identified using Hickman (1993), Kearney and Peebles (1960), and recent treatises; nomenclature follows the USDA Plant database (http://plants.usda.gov/).

Vegetation was harvested from December 15 - 24th 2008. Individual plants were counted and heights measured. Aboveground plant material was clipped at the soil surface and separated by species, by pot, into paper bags. Plants were dried at 80° C in an oven for 48 hours in paper bags and weighed to determine aboveground plant dry weight.

Root biomass was measured in January 2008. Because soils had been compacted from watering and root growth, pots were cut into quarter sections using a handsaw. We extracted roots from one quarter-section using gentle water pressure and sieves. Root material was not separated by species. The extracted roots were laid out to dry for 24 hours and placed in paper bags labeled with pot information. Roots were dried at 60 ° C in an oven for 48 hours and then weighed to determine dry weight. Because we only captured one-quarter the roots, values were multiplied by 4 for data analysis comparing above and below ground biomass allocation.

Experimental Design: Field Studies

As a further test, we sampled streamside vegetation from two rivers, the effluent-dominated Santa Cruz River and perennial and intermittent sections of the San Pedro River, during pre- and post-monsoon seasons in 2007 and 2008. Herbaceous cover by species was visually estimated in 1-m^2 plots within two meters of the low flow channel. Three plots were sampled on each bank at three transects per site, for a total of nine plots per site. Cover was quantified using modified Braun-Blanquet cover classes (1-5, 5-25, 50-75, 75-100%) (Braun-Blanquet, 1932). Voucher specimens were collected and placed in the Arizona State University herbarium.

Data Analysis

Species richness, biomass, plant height and density were compared across nutrient treatments within each river using two-factor ANOVA in PASW 18 (alpha of 0.05). Data were assessed for normality using histograms and quantile-quantile plots, and transformed when necessary. Levene's test for equality of variances was used to test for homogeneity of variances.

To determine how distinct the plant communities were among treatments within each river, Bray-Curtis similarity index was calculated in Estimate S 8.2.0 (Magurran, 2004). To identify how nutrient concentrations correlate with community composition and biomass response, data were analyzed using non-metric multidimensional scaling in PC-ORD 5.

We classified plants into water-quantity based functional groups based on probability of occurrence in wetlands for the Southwestern region (http://plants.usda.gov/), wherein we designated obligate and facultative wetland species as hydric, facultative and facultative upland species as mesic, and upland species as xeric. We then calculated weighted-average wetland indicator scores for the experimental treatments and for the field data.

Finally, we assigned modified Ellenberg N (Ellenberg, 1979) scores to assess shifts in community composition and dominance. The Ellenberg Index is a comprehensive indicator system that describes the response of individual species to a range of ecological conditions (including nitrogen) for vascular plants of central Europe. Ellenberg N scores have been used to assess both regional and local scale changes and have correlated well with measured N deposition (Ellenberg, 1979). We assigned N scores to species using either data in the Ellenberg index or, for genera that could not be found in the index, we estimated modified Ellenberg N scores using biomass and density as response indicators. We calculated weighted average N-scores so that the overall community has a score on a scale of nutrient poor to nutrient rich (Ellenberg, 1979; Ellenberg *et al*., 1991). Ellenberg N scores were calculated for commonly occurring species in the greenhouse experiment treatments (≥ 3 stations) and in the streamside plant communities (≥ 3 sites) on our effluent-dominated study river, the Santa Cruz River, and its control, the San Pedro River.

RESULTS

Greenhouse experiment: Seed banks and hydrologic stream type

Within the no-nutrient control, biomass differed significantly across the three seed banks (Figure 11A; ANOVA: $F_{2,8}=5.957$, $P=0.038$), indicating that hydrologic setting alone influences riparian seed banks and overall plant community response to the wetting of soils. Biomass was nearly two times higher in the two seed banks with perennial stream flows. A Tukey means separation test revealed a significant difference between the effluent-dominated river and the ephemeral river (Table III).

Species richness (Figure 11B) and plant density (Figure 11C) also differed significantly across river types (ANOVA: $F_{2,8}$=10.5, *P*=0.011; $F_{2,8}$=8.267, *P*=0.019 respectively). Differences in richness were significant between the ephemeral river seed bank and those from the systems with higher water availability (Table III). Richness was highest in the ephemeral system, with an average of 7 species per pot, but plant density was lowest in this seed bank, with an average of 15 individuals per pot. Plant density was greatest in the perennial system, with a mean of 46 individuals recorded per pot while the effluent-dominated system averaged 36 individuals.

Composition differed among the three systems based on moisture class requirements. The ephemeral system was dominated by xeroriparian species, with an average wetland indicator score of 4.2, while systems with perennial stream flows were dominated by hydric species, with an average wetland indicator score of 1.8 (Figure 12).

Greenhouse experiment: Nutrients and community response

Biomass. Nitrogen had significant effects on biomass, plant height and shoot:root ratios for all rivers (Table IV). Regardless of river setting, as nitrogen concentrations increased, biomass increased. Highest biomass occurred in the pots with highest nitrogen and intermediate phosphorus concentrations. Biomass in the ephemeral system was about half as great as the effluent-perennial and perennial rivers (Figure 13A). In both perennial river seed banks, there were significant differences in biomass response between low and medium, and low and high nitrogen treatments (Tables V, VI, VII).

Phosphorus trends revealed that biomass was highest at intermediate concentrations in all three seed banks (Figure 14A). In both systems with perennial flow, however, biomass response was greatest at the high nitrogen, medium phosphorus concentrations, while the ephemeral system was greatest at medium phosphorus and medium nitrogen concentrations.

Plant height. Higher nitrogen concentrations significantly increased average plant height (Figure 13B). In the effluent-perennial seed bank, there were significant differences in plant height for all three nitrogen treatments (Table IV). Plant heights were greatest at medium and high phosphorus concentrations in the effluent perennial and perennial seed banks (Figure 14B).

Shoot:root ratios. Shoot:root ratios increased as nitrogen increased for all three rivers, further indicating that nitrogen is the major growth-limiting mineral element (Figure 13C). When this resource is scarce, plants often allocate a greater proportion of their biomass to the root system. In this case, as nitrogen increases in availability, allocation to aboveground biomass increases. Patterns in above and below ground biomass allocation were less clear with phosphorus, although ratios appeared to be greatest at intermediate P concentrations (Figure 14C).

Plant density. Plant densities decreased with increasing nitrogen within each river type (Figure 15A). Phosphorus trends were less clear, with density highest at lower nitrogen and intermediate phosphorus levels (Figure 16A). In the ephemeral and perennial seed banks, plant density was significantly different among low and medium and low and high P concentrations, while the significant differences in the effluent-dominated system were between low and high P concentrations (Tables V, VI, VII).

Richness. A total of fifty species were identified in the experiment, with 32 species in the ephemeral-river seed bank and 23 and 36 species in the perennial and effluent-dominated systems, respectively. Fourteen species were non-native (Appendix II). The ephemeral and perennial seed banks differed in average number of species across treatments, with values highest in the intermediate nitrogen and phosphorus treatments (Figures 15B &16B). There were no significant differences in species richness among treatments for the effluent-perennial seed bank.

Composition. For all river types, there was dissimilarity across nutrient treatments, based on the Bray-Curtis similarity index (Tables VIII, IX, X).Increasing nutrient concentrations led to decreasing similarity in composition for all three seed banks. Non-metric multidimensional scaling showed that increasing concentrations of nitrogen and phosphorus explained much of the variation in community response, but was dependent on seed bank type (Figures 17, 18, 19). The ephemeral seed bank was unusual in that phosphorus and nitrogen both had strong influences on community composition. The patterns in the effluent-perennial seed bank indicate a strong shift toward nitrophilic species in stations receiving nitrogen-enriched water.

Modified Ellenberg N scores further substantiated a shift in composition toward nitrophilic, species in treatments with higher nitrogen (Figure 20). Although these shifts were apparent in all hydrologic settings, they varied in extent. The treatments with higher nitrogen concentrations in the perennial and effluent-dominated seed banks were dominated by nitrophilic species such as *Conium maculatum, Echinochloa sp., Nasturtium officianale, and Polygonum lapathifolium.* Of the fourteen non-native species identified in the experiment, eleven had Ellenberg scores greater than 6. Ellenberg N scores were highest in the effluent-dominated seed bank, with an average score just under 7 on a scale from 1 to 9, with higher numbers indicating higher nitrogen affinity. The perennial river had mean Ellenberg N scores of just above 5 while the ephemeral river scores were around 4 (Table XI).

Field studies: Streamside plant communities

Streamside plant communities followed similar patterns to the experimental seed banks, in that plant communities along the Santa Cruz River were dominated by nitrophilic species such as *Polygonum lapathifolium* and *Conium maculatum* (Figure 21). The average Ellenberg N score for the 2008 Santa Cruz River streamside data fell between 7 and 8, which indicates species more tolerant of nutrient-rich conditions. In contrast, the average Ellenberg N scores were less than 6 for the perennial control river (San Pedro) and vegetation along the control river had higher species diversity but lower biomass than the effluent system.

DISCUSSION

Because nitrogen is required by plants in the greatest quantity relative to other nutrients, and is often limiting to productivity (Chapin *et al*., 1987, Vitousek and Howarth, 1991; Venterink *et al.*, 2003), species were expected to show an increase in primary production with the addition of N. Biomass and plant height increased with higher nitrogen concentrations for all three seed bank types, supporting our hypothesis. These patterns were similar regardless of hydrologic setting; however, the amount of biomass response was significantly different based on site hydrology. According to our data, releasing treated wastewater into an ephemeral waterway will result in less than half the biomass response than in waterways with shallow groundwater tables, at least during the initial months. Longer-term patterns will depend on the degree to which the effluent-receiving site is connected to species-rich sites which can serve as a source of colonization for plants that thrive under conditions of abundant water and nutrients. Maintaining longitudinal and vertical connectivity in riverine ecosystems will increase dispersal, allow for colonization after disturbance events, and maintain the biodiversity necessary for ecosystem function and community resilience in novel environments, such as effluent-dominated waterways (Loreau *et al*., 2003)

Although some wetlands and some wetland species have shown high sensitivity to P (Chiang *et al*., 2000; Noe *et al*., 2001), phosphorus patterns were less distinct for the desert riparian systems we studied. Concomitant with the nitrogen-fueled increase in biomass was a decrease in species richness and low plant density at the medium and high P concentrations. This pattern may indicate a threshold for P toxicity in treated wastewater, particularly in the ephemeral system, which showed a significant decrease in stem density and richness at the higher nutrient ratios. These patterns in species richness observed in this study have been demonstrated in many terrestrial and wetland fertilization studies (Tilman, 1987; Bedford *et al*., 1999; Day *et al*., 2004). Species richness is expected to be highest at intermediate levels of fertility and decrease with higher plant production (Bowman *et al*.1993). Based on the results of this study and others (Drexler and Bedford, 2002), we speculate that constraints on species richness will occur at nitrogen levels above 10 mg/L in waterways receiving treated wastewater.

Shoot:root patterns revealed that plants allocated relatively more energy into root biomass at lower nutrient concentrations and that shoot production increases as nitrogen increases regardless of hydrologic setting. As nitrogen concentrations increased, a greater proportion of energy was invested into shoot biomass production, particularly in the effluent and perennial seed banks. Models of plant allocation to shoot or root growth have shown that an individual plant will respond to a light or CO_2 limitation with increased shoot growth; whereas, a water or nutrient limitation will result in greater allocation to root growth (Brouwer, 1963; Brouwer, 1983; Tilman, 1988). When nutrients are scarce, a species may gain dominance if it is capable of allocating more biomass to root production, thereby acquiring nutrients and reducing the pool of nutrients available to competitors (Gleeson and Tilman, 1990, Craine *et al.*, 2005).

Shifts in plant community composition correlated strongly with increasing nutrients, particularly nitrogen. By the end of the experiment, treatments with more nitrogen-tolerant species had greater individual mass and lower stem density, indicating that nitrophiles likely modulate many responses to N addition. Successful acquisition or conservation of limiting resources requires that a species possess certain advantageous physiological and structural traits (Chapin *et al.*, 1986). However, Diekmann & Falkengren-Grerup (2002) found that many life history traits poorly predicted species responses to elevated N, and instead developed ‘attribute syndromes’ to predict suites of traits favored with N addition. From this perspective, the community can be viewed as an expression of multiple suites of traits that are either reinforced or become obsolete with changing conditions, or disturbances. In effluent-dominated waterways, ecological conditions are altered through the creation of perennial stream flows and increased nutrient availability, which modifies the dynamics for streamside community development.

Explanations for the processes driving the patterns of riparian plant communities are of importance to managers, some of whom have approached the community change by attempting to eradicate non-native species. In arid and semi-arid ecosystems, the mitigation of two key limiting resources, water and nutrients, shifts the competitive balance between functional types and between non-native and native plants. Research on invasibility has shown that opportunistic plants take advantage of high resource availability and that low resource availability is associated with low invasibility (Planty-Tabacchi *et al*., 1996; Alpert *et al*., 2000; Kolb *et al*., 2002; Davis *et al*., 2003; Richardson, 2006). Greenhouse experiments have revealed that high nutrient or water availability can increase the ability of certain non-nativeplant species to compete with natives (Wedin & Tilman, 1993; Claassen & Marler, 1998). Field experiments have shown interactive effects of resource availability and competition on invasibility (Burke & Grime, 1996; White *et al.* 1997;Thompson *et al*. 2001). In the case of the effluent-dominated Santa Cruz River, long-term nutrient enrichment of the stream (with discharge having begun in 1951) has led to a shift toward nitrophilic species, many of which are non-native.

This synthesis offers insight for resource managers and decision makers on how to utilize treated wastewater to promote the establishment of vegetation dependent upon hydrologic setting. From this study we also provide information that illustrates how water quality gradients influence the structure and function of the herbaceous plant community in waterways receiving treated wastewater. Current and future wastewater treatment plants upgrades on the upper and lower Santa Cruz River offer the opportunity to further examine the effects of water quality on riparian streamside communities as reductions in n-load may shift non-nitrophiles to replace nitrophiles.

CONCLUSIONS

As anthropogenic nitrogen inputs continue to equal or exceed natural N inputs in many ecosystems and as larger scale restoration is planned for entire landscapes, this study reveals that water quality and hydrologic setting are important ecological variables influencing herbaceous plant community development and population-level processes in waterways receiving treated wastewater. Our findings of the effects of N and P enrichment and variation within different hydrologic settings have important implications for understanding the potential outcomes of treated wastewater discharge on riparian plant communities. First, they call attention to the need for local assessments of ecological limiting factors, such as hydrogeomorphic setting, in effectively predicting quantity and quality of riparian habitat response. Second, the dual importance of N and P limitation indicates that alterations of a particular nutrient may result in quantitative changes, such as biomass production as well as qualitative shifts, such as the composition of riparian plant communities or increases in non-native species. Finally, our results reveal that enrichment by either N or P can increase primary production but that nitrogen appears to have a stronger influence on level of production, largely due to nitrophilic species capable of outcompeting other plants less-equipped to take advantage of the excess nutrients.

Table II. Experimental design of N:P treatments for three different seed bank types (ephemeral, effluent-dominated, and perennial). Each treatment was delivered to a station containing 9 pots with three replicates of each seed bank type. n = 81 (experiment); n = 27 (within seed bank).

	Low P	***Medium P***	***High P***
Low N	1 N mg/L 0.1 P mg/L	1 mg/L N 4 mg/L P	1 mg/L N 6 mg/L P
Medium N	10 mg/L N 0.1 mg/L P	10 mg/L N 4 mg/L P	10 mg/L N 6 mg/L P
High N	30 mg/L N 0.1 mg/L P	30 mg/L N 4 mg/L P	30 mg/L N 6 mg/L P

Table III. Comparison of riparian plant community response (biomass, richness, density, plant height) to the introduction of water in three different hydrologic settings. Bold values indicate a significant difference between river types (Tukey test, P<0.05).

	(I) Hydrology	(J) Hydrology	*Mean difference (I-J)*	*Sig*
Biomass	Ephemeral	Effluent-dominated	-1.257	**0.045**
		Perennial	-1.110	0.071
	Effluent-dominated	Perennial	0.147	0.929
Richness	Ephemeral	Effluent-dominated	2.000	**0.054**
		Perennial	3.000	**0.010**
	Effluent-dominated	Perennial	1.000	0.355
Density	Ephemeral	Effluent-dominated	-19.000	0.106
		Perennial	-31.000	**0.016**
	Effluent-dominated	Perennial	12.000	0.331
Plant height	Ephemeral	Effluent-dominated	6.533	0.069
		Perennial	7.247	**0.047**
	Effluent-dominated	Perennial	-0.713	0.950

Table IV. ANOVA results for community variables across varying concentrations of nitrogen and phosphorus. (Bold font denotes significance, alpha = 0.05, n = 27)

		Ephemeral		***Effluent dominated***		***Perennial***	
Biomass	**df**	**F**	**P**	**F**	**P**	**F**	**P**
N	2	4.513	**0.026**	8.054	**0.003**	25.737	**<0.001**
P	2	0.567	0.577	1.878	0.182	4.521	**0.026**
N*P	4	1.466	0.254	1.107	0.384	3.183	**0.038**
Plant height							
N	2	8.714	**0.002**	43.636	**<0.001**	62.113	**0.02**
P	2	0.016	0.984	2.638	0.099	4.877	**<0.001**
N*P	4	0.812	0.534	2.764	**0.059**	2.662	0.066
Shoot:root							
N	2	1.825	0.19	9.945	**0.001**	40.326	**<0.001**
P	2	0.499	0.615	3.733	**0.044**	2.061	0.156
N*P	4	0.943	0.462	5.332	**0.005**	3.021	**0.045**
Richness							
N	2	9	**0.002**	0.103	0.903	5.292	**0.016**
P	2	0.114	0.893	1.338	0.287	2.542	0.107
N*P	4	0.741	0.577	3.588	**0.026**	0.354	0.838
Density							
N	2	11.123	**0.001**	7.281	**0.005**	13.748	**<0.001**
P	2	1.301	0.297	0.576	0.572	0.777	0.474
N*P	4	1.372	0.283	1.593	0.219	0.964	0.451

Table V. Riparian plant community response (biomass, plant height, shoot:root ratio, richness, and density) to varying nutrient concentrations for the ephemeral system. Bold values indicate a significant difference between river types (Tukey test, P<0.05).

	(I) Nitrogen	(J) Nitrogen	*Mean difference (I-J)*	*Sig*	(I) Phosphorus	(J) Phosphorus	*Mean difference (I-J)*	*Sig*
Biomass	Low	Med	-1.956	**0.020**	Low	Med	-0.6033	0.632
		High	-0.8867	0.382		High	-5.989	0.636
	Med	High	1.0689	0.255	Med	High	0.0044	1.000
Plant Height	Low	Med	-1.623	**0.010**	Low	Med	-0.0889	0.982
		High	-1.894	**0.003**		High	-0.0389	0.997
	Med	High	-0.2711	0.847	Med	High	0.05	0.994
Shoot:root	Low	Med	-0.0338	0.980	Low	Med	-0.1765	0.587
		High	-0.3078	0.217		High	-0.0863	0.878
	Med	High	-0.2739	0.292	Med	High	-0.2739	0.867
Richness	Low	Med	1	0.446	Low	Med	0	1.000
		High	3.333	**0.002**		High	0.3333	0.911
	Med	High	2.333	**0.025**	Med	High	0.3333	0.911
Density	Low	Med	1.4489	**0.035**	Low	Med	-0.8522	0.268
		High	2.4878	**0.001**		High	-0.3711	0.766
	Med	High	1.0389	0.151	Med	High	0.4811	0.642

Table VI. Riparian plant community response (biomass, plant height, shoot:root ratio, richness, and density) to varying nutrient concentrations for the effluent-dominated system. Bold values indicate a significant difference between river types (Tukey test, P<0.05).

	(I) Nitrogen	(J) Nitrogen	*Mean difference (I-J)*	*Sig*	(I) Phosphorus	(J) Phosphorus	*Mean difference (I-J)*	*Sig*
Biomass	Low	Med	-1.5989	**0.030**	Low	Med	-0.5611	0.595
		High	-2.2133	**0.003**		High	0.5422	0.615
	Med	High	-0.6144	0.539	Med	High	1.1033	0.157
Plant Height	Low	Med	-1.6389	**p<.001**	Low	Med	-0.5878	0.134
		High	-2.6856	**p<.001**		High	-0.0233	0.996
	Med	High	-1.0467	**0.005**	Med	High	0.5644	0.154
Shoot:root	Low	Med	-0.4124	**0.014**	Low	Med	-0.3453	**0.041**
		High	-0.5602	**0.001**		High	-0.2467	0.169
	Med	High	-0.1479	0.505	Med	High	0.0986	0.733
Richness	Low	Med	-0.2222	0.953	Low	Med	0.1111	0.988
		High	-0.3333	0.897		High	-1	0.394
	Med	High	-0.1111	0.988	Med	High	-1.1111	0.321
Density	Low	Med	0.6144	0.217	Low	Med	0.2078	0.827
		High	1.3433	**0.003**		High	-0.17	0.880
	Med	High	0.7289	0.125	Med	High	-0.3778	0.543

Table VII. Riparian plant community response (biomass, plant height, shoot:root ratio, richness, and density) to varying nutrient concentrations for the perennial system. Bold values indicate a significant difference between river types (Tukey test, P<0.05).

	(I) Nitrogen	(J) Nitrogen	*Mean difference (I-J)*	*Sig*	(I) Phosphorus	(J) Phosphorus	*Mean difference (I-J)*	*Sig*
Biomass	Low	Med	-2.35	**p<.001**	Low	Med	-1.1589	**0.030**
		High	-2.75	**p<.001**		High	-0.1844	0.897
	Med	High	-0.4	0.607	Med	High	0.9744	0.074
Plant Height	Low	Med	-2.9911	**p<.001**	Low	Med	-0.9589	**0.018**
		High	-3.0667	**p<.001**		High	-0.6556	0.120
	Med	High	-0.0756	0.969	Med	High	0.3033	0.607
Shoot:root	Low	Med	-0.7688	**p<.001**	Low	Med	-0.205	0.166
		High	-0.8908	**p<.001**		High	-0.1676	0.289
	Med	High	-0.122	0.506	Med	High	0.0374	0.936
Richness	Low	Med	-0.6667	0.314	Low	Med	-0.4444	0.586
		High	0.7778	0.215		High	0.5556	0.440
	Med	High	1.4444	**0.012**	Med	High	1	0.090
Density	Low	Med	1.7389	**0.003**	Low	Med	0.2233	0.873
		High	2.24	**p<.001**		High	0.5556	0.446
	Med	High	0.5011	0.516	Med	High	0.3322	0.743

Table VIII. The Bray-Curtis index for the ephemeral seed bank shows that similarity decreases with increasing nutrients across all three seed banks. Dissimilarity is highest between the low and high nitrogen concentrations.

	Low N Low P	*Low N Med P*	*Low N High P*	*Med N Low P*	*Med N Med P*	*Med N High P*	*High N Low P*	*High N Med P*	*High N High P*
Low N Low P	1								
Low N Med P	0.414	1							
Low N High P	0.175	0.275	1						
Med N Low P	0.341	0.153	0.354	1					
Med N Med P	0.145	0.251	0.303	0.508	1				
Med N High P	0.115	0.128	0.188	0.266	0.344	1			
High N Low P	0.176	0.282	0.351	0.252	0.208	0.172	1		
High N Med P	0.087	0.107	0.400	0.411	0.282	0.119	0.190	1	
High N High P	0.255	0.195	0.197	0.490	0.446	0.294	0.212	0.137	1

Table IX. Bray-Curtis index for the effluent-dominated seed bank show that similarity decreases with increasing nutrient concentrations across all three seed banks. Dissimilarity is highest between the low and high nitrogen concentrations.

	Low N Low P	*Low N Med P*	*Low N High P*	*Med N Low P*	*Med N Med P*	*Med N High P*	*High N Low P*	*High N Med P*	*High N High P*
Low N Low P	1								
Low N Med P	0.667	1							
Low N High P	0.547	0.479	1						
Med N Low P	0.458	0.402	0.553	1					
Med N Med P	0.395	0.376	0.560	0.873	1				
Med N High P	0.353	0.394	0.490	0.494	0.539	1			
High N Low P	0.446	0.451	0.437	0.588	0.645	0.563	1		
High N Med P	0.310	0.293	0.389	0.605	0.619	0.626	0.566	1	
High N High P	0.352	0.386	0.591	0.511	0.552	0.599	0.514	0.468	1

Table X. The Bray-Curtis index for the perennial seed bank shows that similarity decreases with increasing nutrients across all three seed banks. Dissimilarity is highest between the low and high nitrogen concentrations.

	Low N Low P	*Low N Med P*	*Low N High P*	*Med N Low P*	*Med N Med P*	*Med N High P*	*High N Low P*	*High N Med P*	*High N High P*
Low N Low P	1								
Low N Med P	0.848	1							
Low N High P	0.781	0.835	1						
Med N Low P	0.651	0.540	0.484	1					
Med N Med P	0.525	0.431	0.383	0.687	1				
Med N High P	0.669	0.589	0.520	0.785	0.719	1			
High N Low P	0.815	0.724	0.626	0.738	0.602	0.677	1		
High N Med P	0.415	0.353	0.310	0.582	0.491	0.590	0.443	1	
High N High P	0.548	0.450	0.400	0.768	0.593	0.683	0.598	0.755	1

Table XI. Average Ellenberg N scores by seed bank for each level of nitrogen treatment. The effluent-dominated system was dominated by nitrophilic species.

	Low N	**Med N**	**High N**
Ephemeral	3.9	4.8	4.4
Effluent-dominated	5.1	6.2	7.3
Perennial	4.8	5.5	5.4

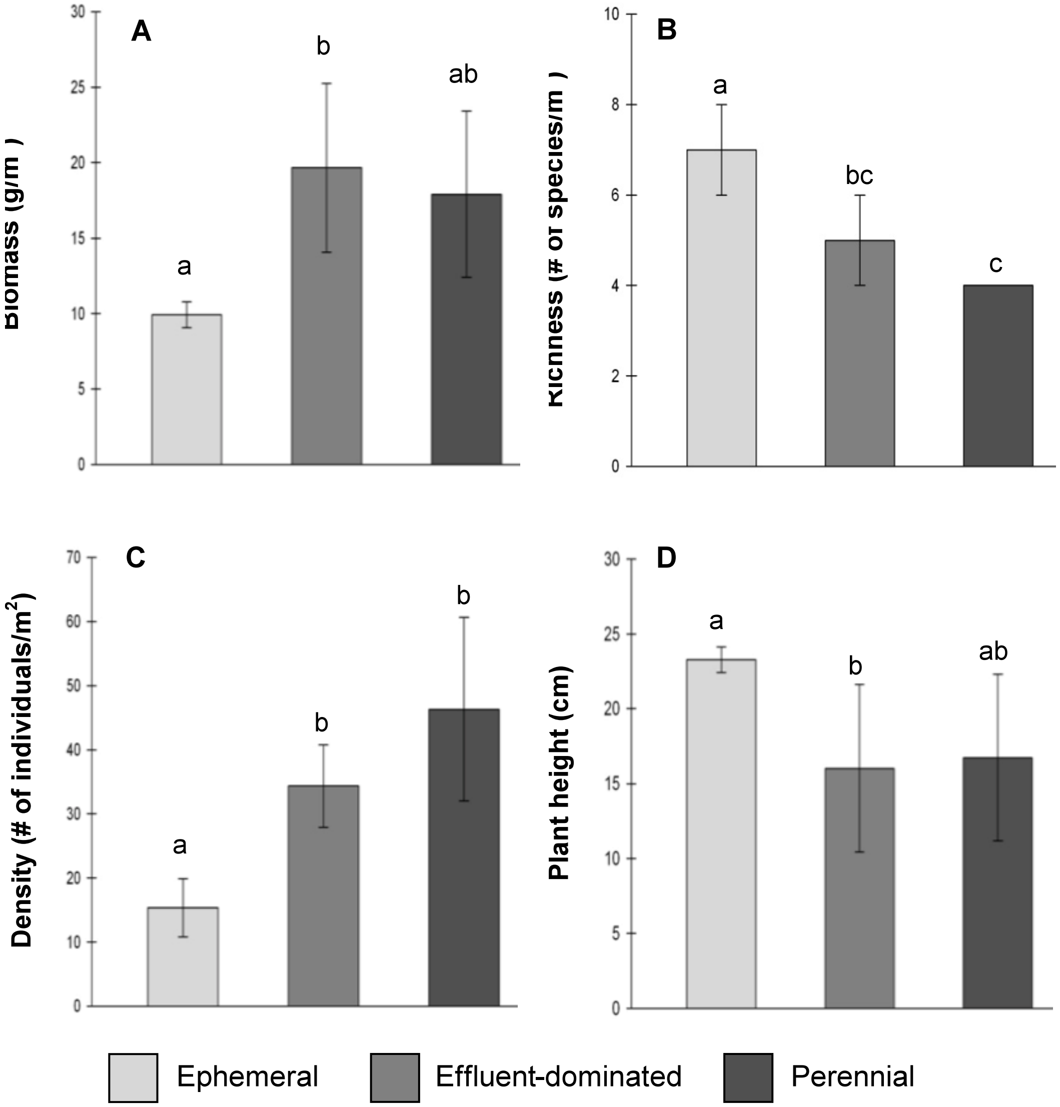


Figure 11. When water is introduced to three different hydrologic settings, (ephemeral, effluent dominated and perennial), biomass (A) is significantly higher in systems with perennial flows. Species richness (B) is highest in the ephemeral system where water availability is a limiting factor. Density (C) is highest the two systems with perennial base flow. Plant height (D) is highest in the effluent dominated system. Letters indicate significant differences based on Tukey test ($P < 0.05$). (SE = standard error, $n = 9$, alpha = 0.05)

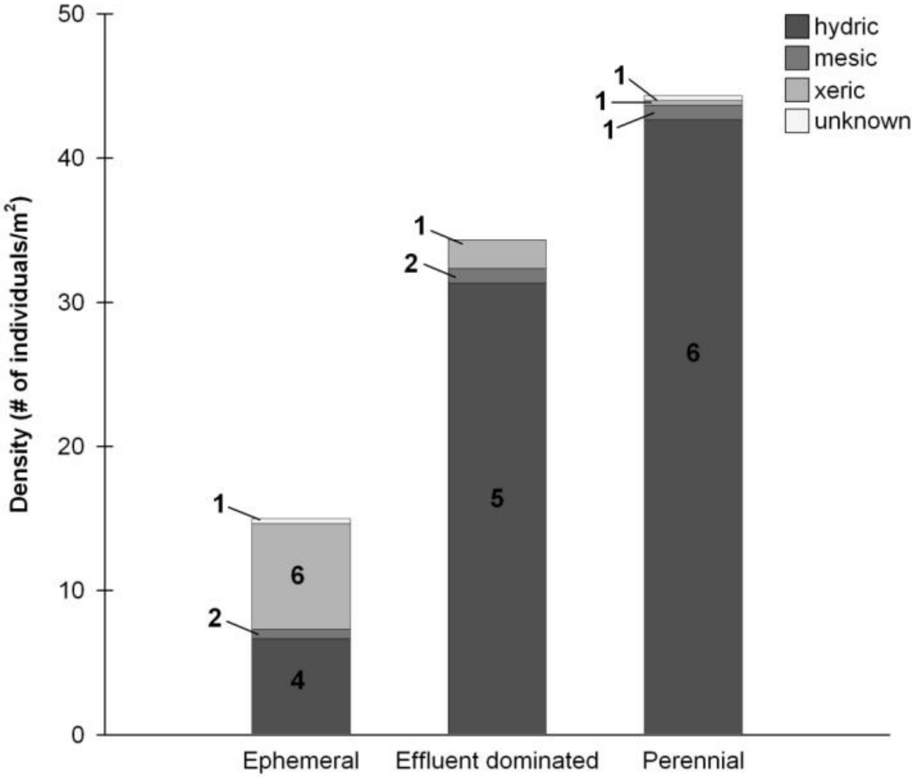


Figure 12. Density partitioned by moisture requirement across river type, with number of species labeled. Seed banks from systems with perennial base flows are dominated by hydric species while the ephemeral seed bank has more xeric species. Data show emergence from the experimental control treatment (water, minimal nutrient addition). Bold numbers indicates species richness per moisture class group.

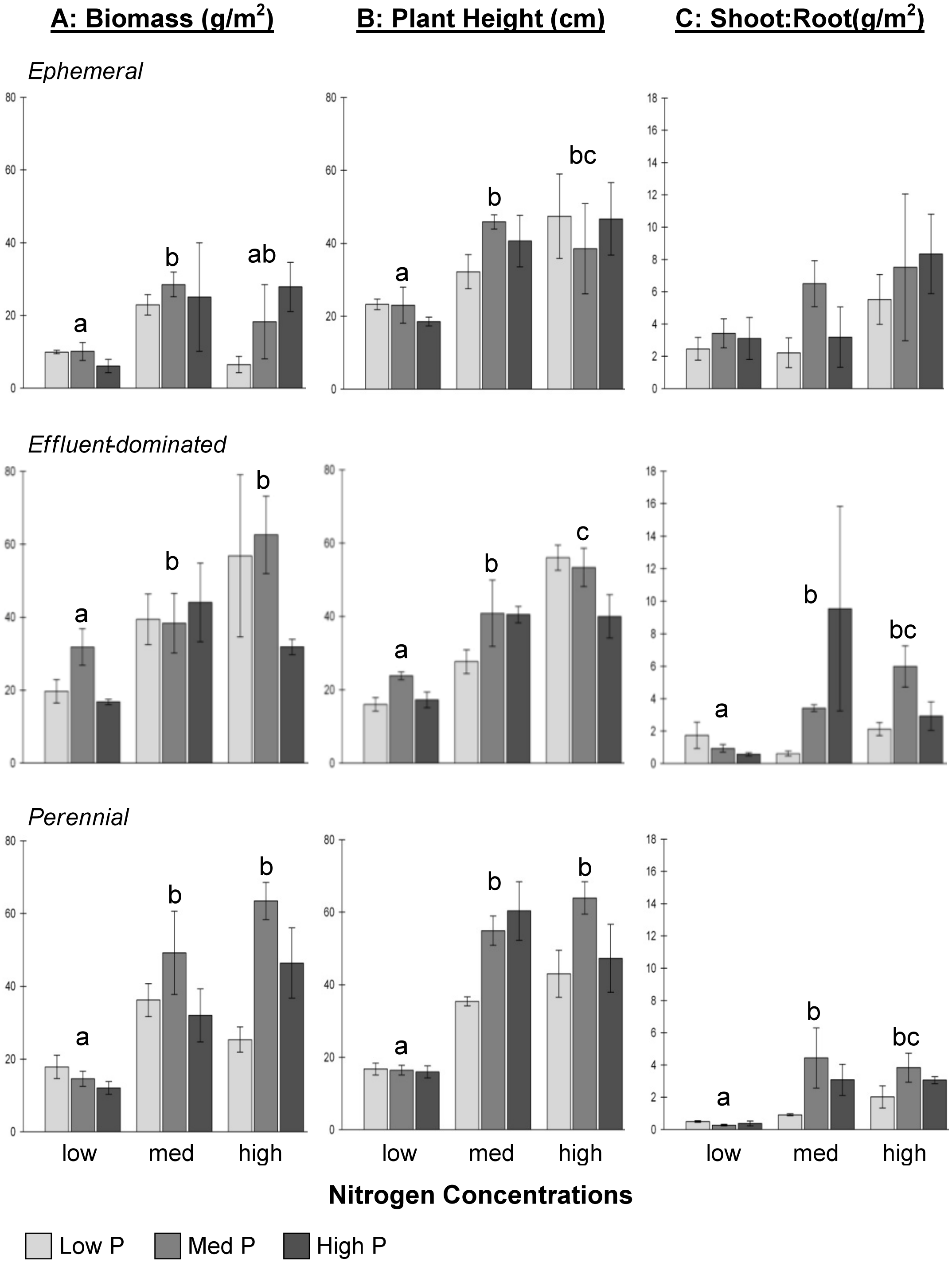


Figure 13. Biomass (A), plant height (B), and shoot:root ratios (C) increased with nitrogen additions across all river types. Data displayed are mean values with standard error (SE) from a two-factor ANOVA with N as the main divisions along the x-axis. Increasing concentrations of P are displayed within each N group. Letters above the bars indicate a significant difference between treatments (Tukey test, P<0.05>)

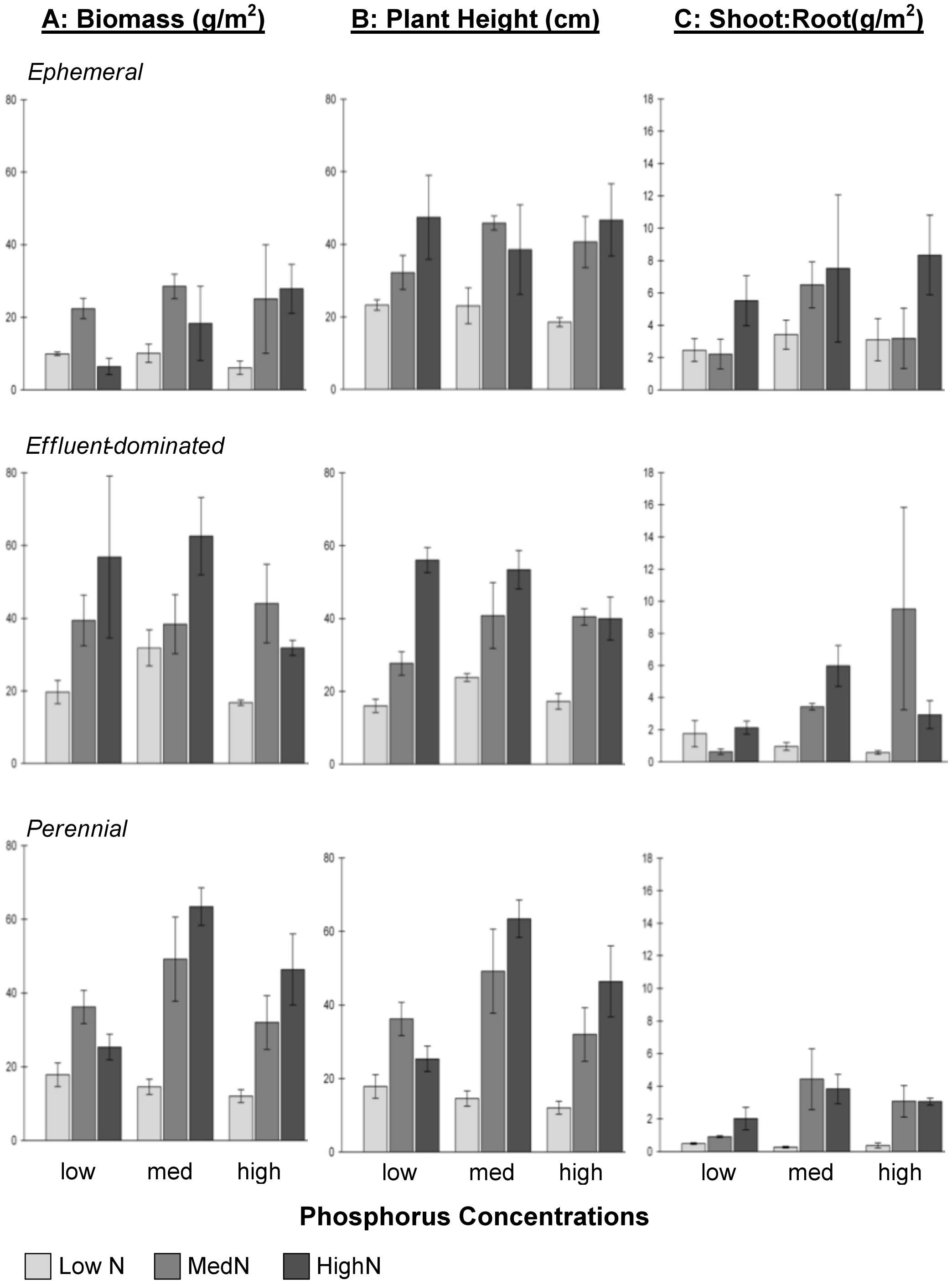
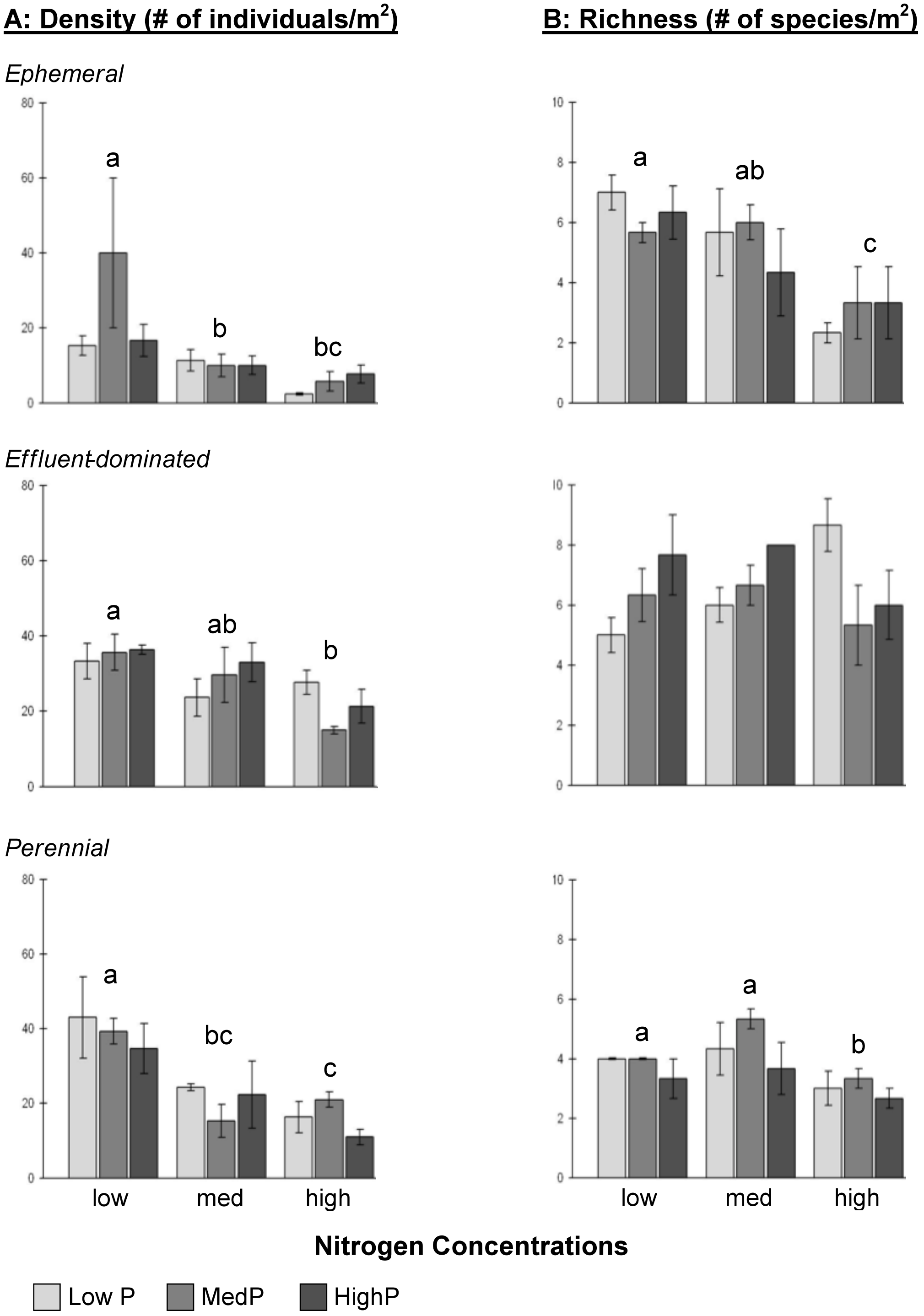


Figure 14. Biomass (A) and plant height (B) were highest at intermediate P concentrations. Shoot:root ratios (C) decreased with increased water availability, although no significant trends emerged with P. Data displayed are mean values with standard error (SE) from a two-factor ANOVA with P as the main divisions along the x-axis. Increasing concentrations of N are displayed within each P group.



A: Density (# of individuals/m^2)

B: Richness (# of species/m^2)

Figure 15. Density (A) and richness (B) decreased with increasing nitrogen across all river types. Data displayed are mean values with standard error (SE) from a two-factor ANOVA with N as the main divisions along the x-axis. Increasing concentrations of P are displayed within each N group.

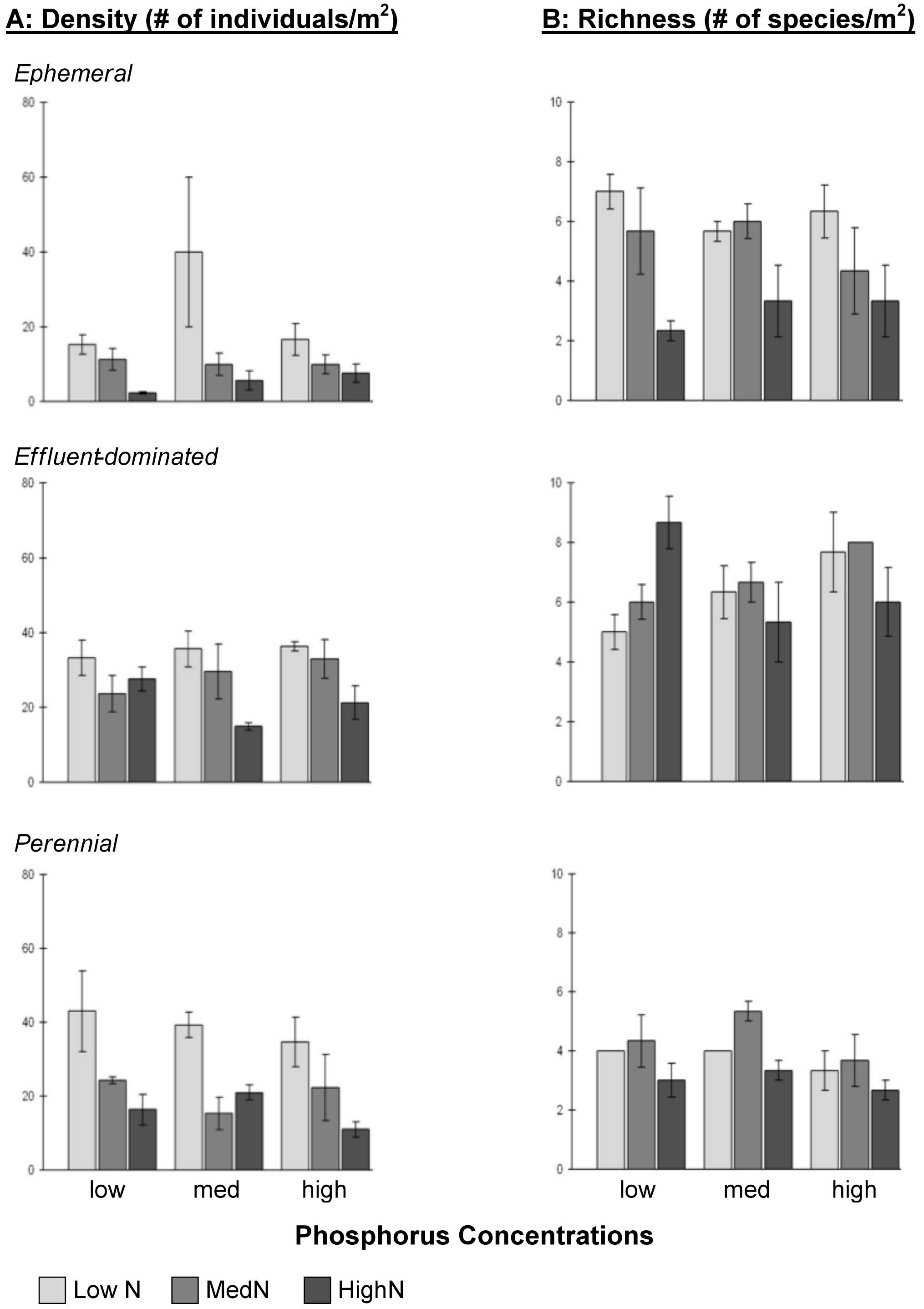


Figure 16. Density (A) and richness (B) decreased with increasing phosphorus across all river types. Data are mean values with standard error (SE) from a two-factor ANOVA with P as the main divisions along the x-axis. Increasing concentrations of N are displayed within each P group. Letters above bar graphs indicate a significant difference between treatments (Tukey test, $P<0.05$).

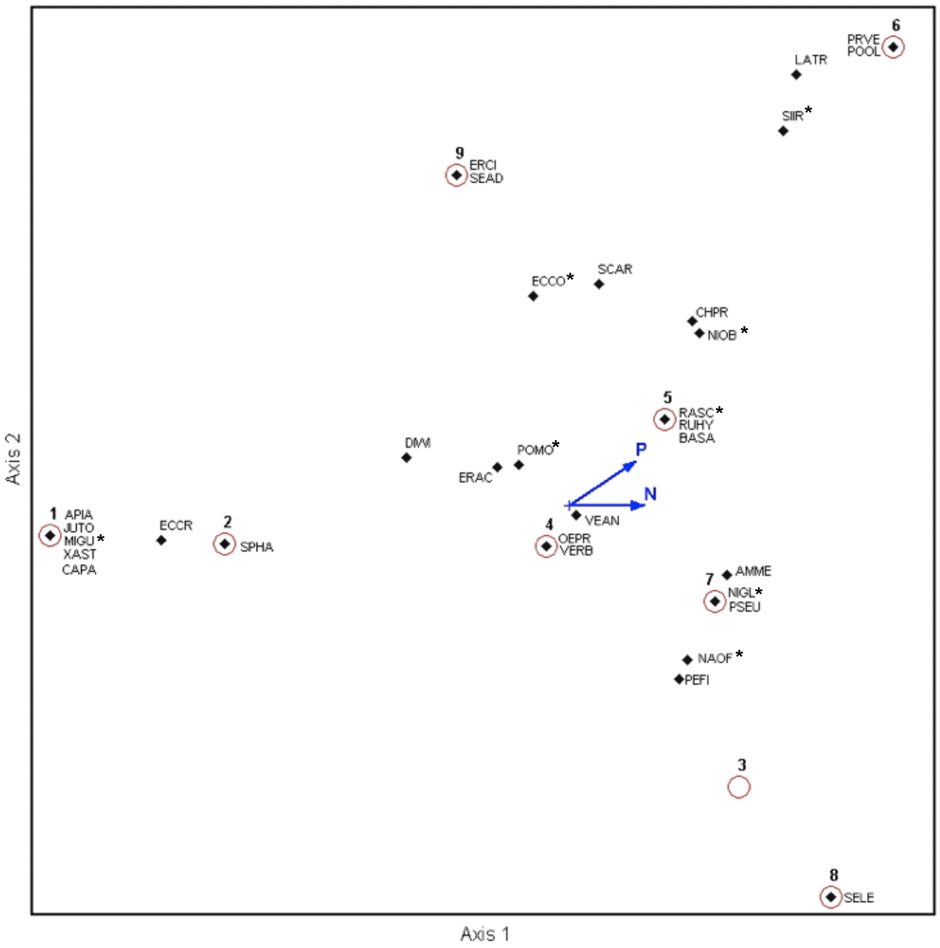


Figure 17. NMS ordination of plots in species space for the ephemeral seed bank. Only common species (occurring >3 stations) are shown. Length of correlation vectors represents the strength of the correlation. Diamond = species, circle = pots. Lines show correlation vectors (radiating from the centroid) of environmental characters with the ordination: Phosphorus (P) and Nitrogen (N). **=nitrophilic species with modified Ellenberg score >6.*

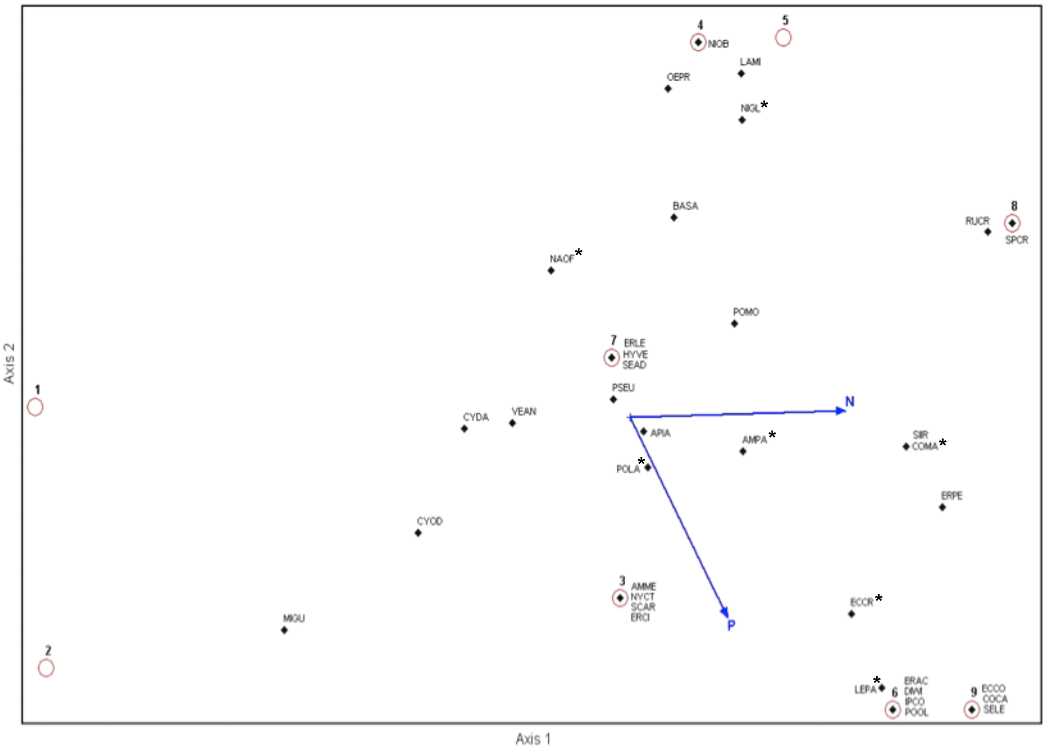


Figure 18. NMS ordination of plots in species space for the effluent-dominated seed bank. Only common species (occurring >3 stations) are shown. Length of correlation vectors represents the strength of the correlation. Diamond = species, circle = pots. Lines show correlation vectors (radiating from the centroid) of environmental characters with the ordination: Phosphorus (P) and Nitrogen (N). *=*nitrophilic species with modified Ellenberg score >6.*

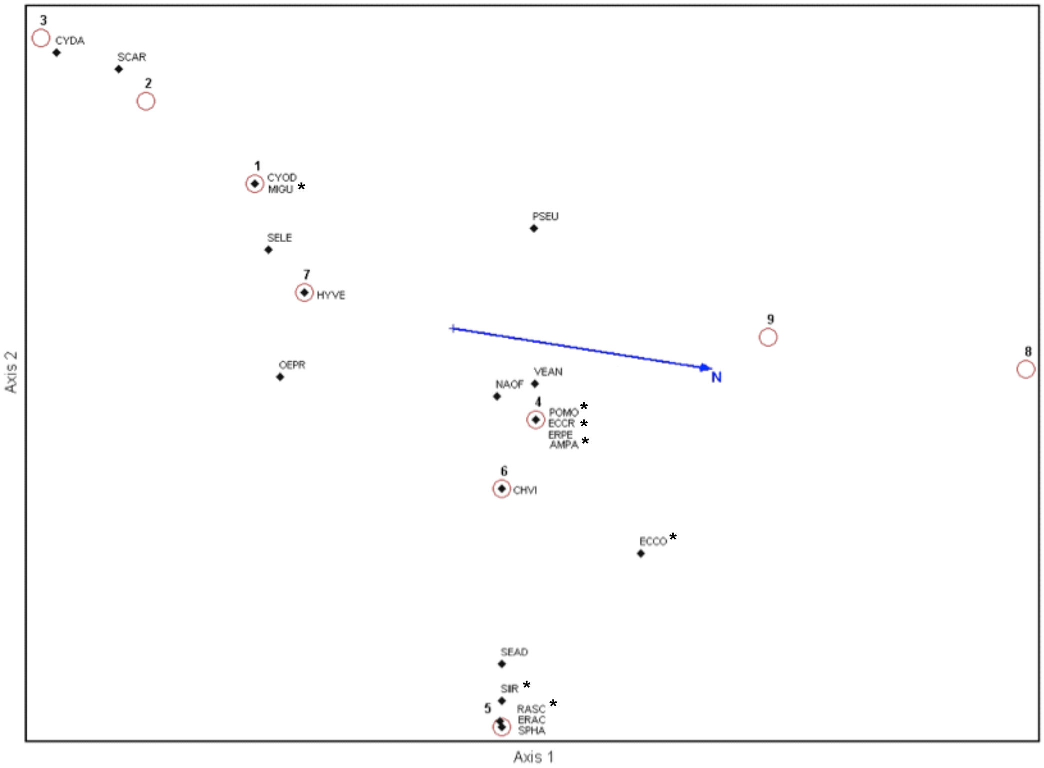


Figure 19. NMS ordination of plots in species space for the perennial seed bank. Only common species (occurring >3 stations) are shown. Length of correlation vectors represents the strength of the correlation. Diamond = species, circle = pots. Lines show correlation vectors (radiating from the centroid) of environmental characters with the ordination: Phosphorus (P) and Nitrogen (N). *=*nitrophilic species with modified Ellenberg score >6.*

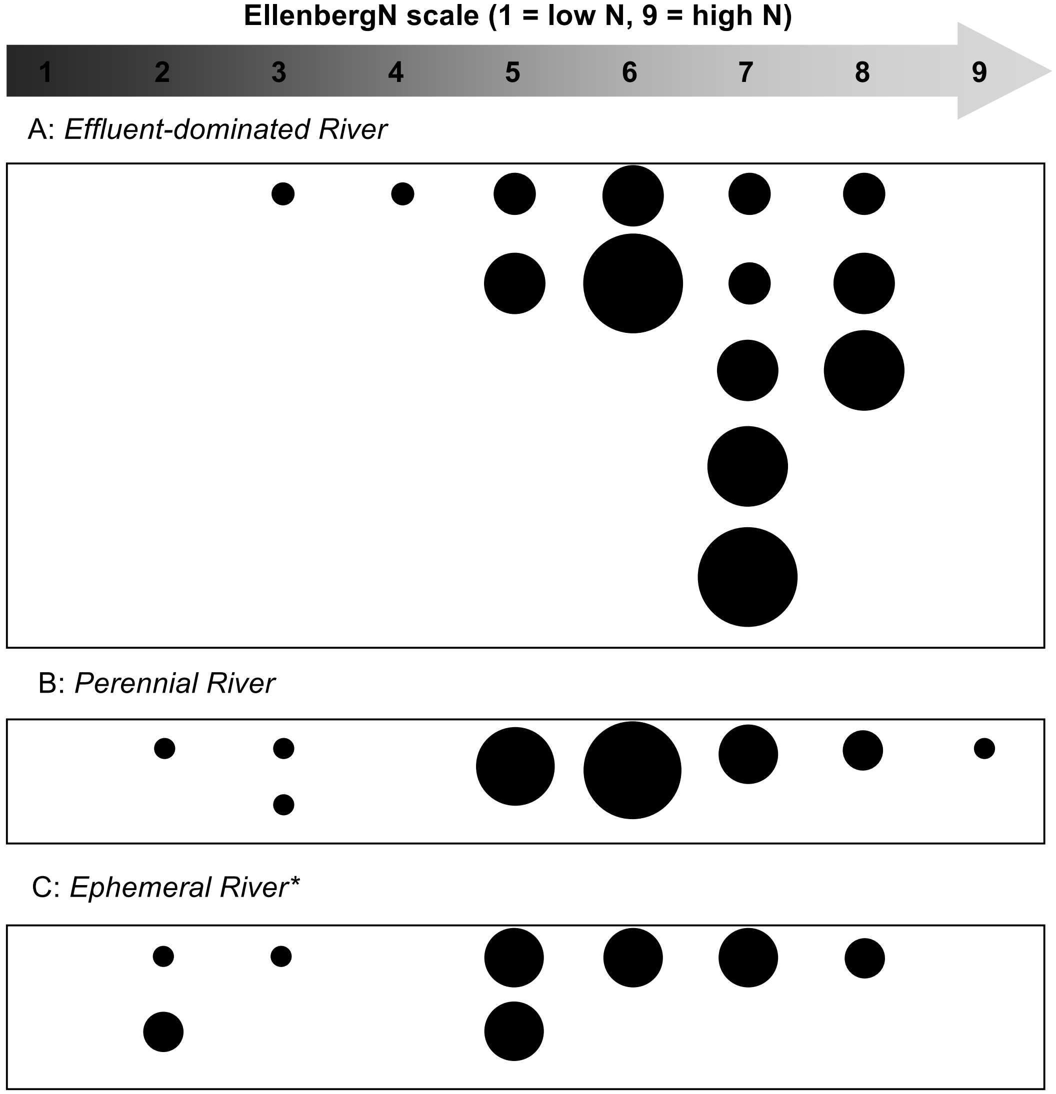
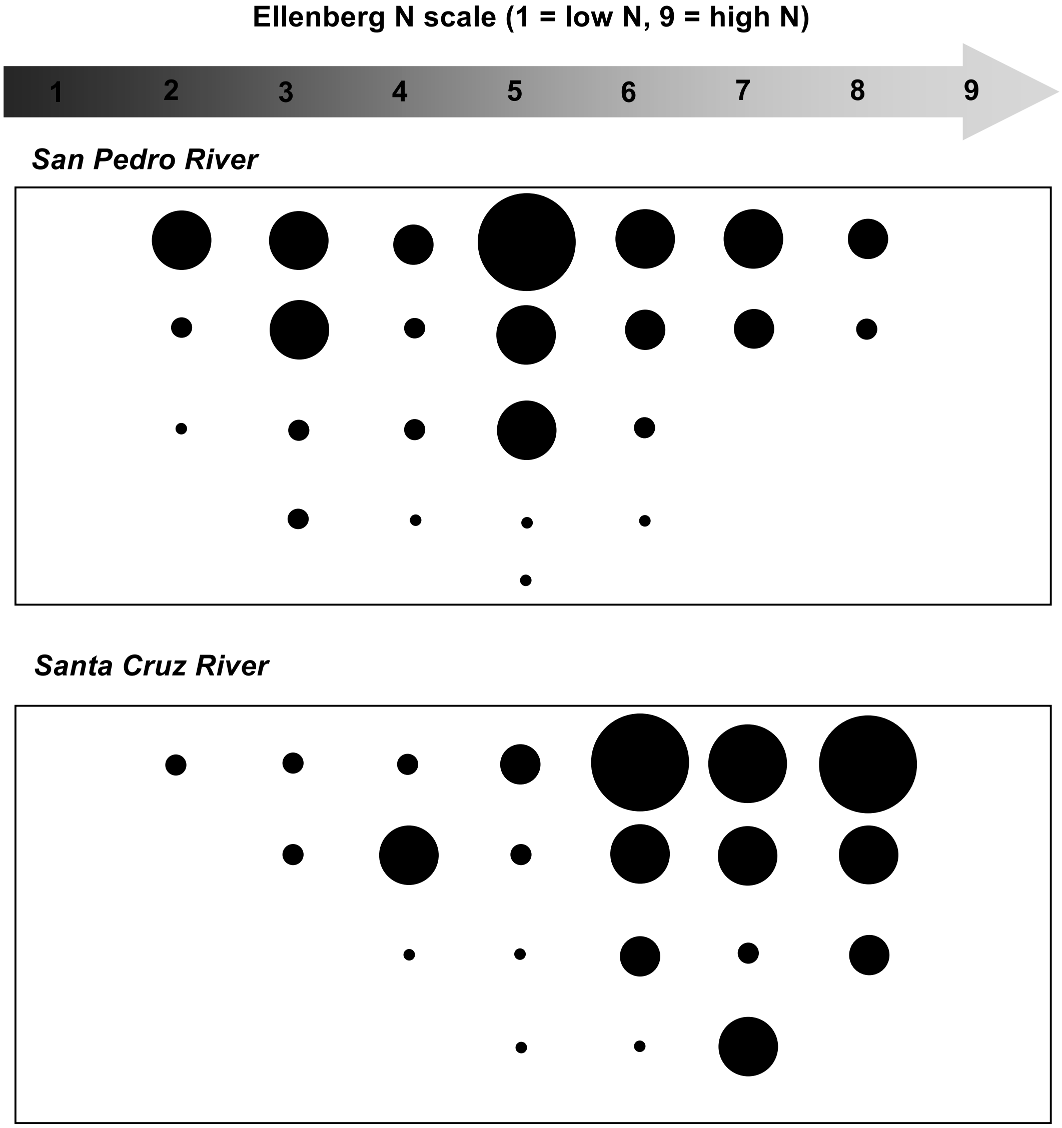


Figure 20. Ellenberg N scores for vegetation response in three different hydrologic settings in the greenhouse experiment. A value of "1" indicates low nitrogen species and a value of "9" indicates high nitrogen species. Each circle represents a commonly (>3 pots) occurring species. The size of the circle indicates aboveground biomass. The effluent-dominated river has a higher biomass response and tendency toward nitrophilic species. (*denotes missing Ellenberg scores)



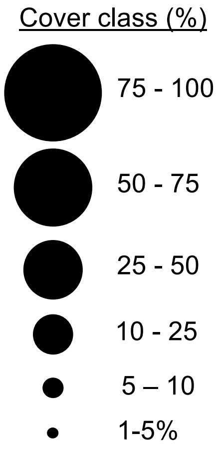


Figure 21. Ellenberg N scores for vegetation response along the effluent-dominated Santa Cruz River and its control, the San Pedro River. A value of "1" indicates low nitrogen species and a value of "9" indicates high nitrogen species. Each circle represents a commonly occurring species (>3 sites). The size of the circle indicates aboveground biomass.

4. LONGITUDINAL AND LATERAL PATTERNS OF HERBACEOUS PLANT COMMUNITIES IN AN EFFLUENT-DOMINATED RIPARIAN ECOSYSTEM

ABSTRACT

Patterns and distributions of herbaceous plant communities in desert riparian zones are often reflective of multiple environmental gradients shaped by connections between vertical, longitudinal, and lateral water movement. Over the past century in the southwestern United States, there have been many anthropogenic alterations to the hydrological processes that shape riparian ecosystems. One change, the release of treated wastewater into nearby river channels, has created perennial base flows and increased nutrient availability in otherwise ephemeral or intermittent channels. While there are many benefits to utilizing treated wastewater for the maintenance of environmental flows, there are numerous unresolved ecohydrological issues regarding the efficacy of the release of surface effluent into groundwater-dependent riparian systems. This study examined how effluent, providing both water and increased nutrient availability, may contribute to restoring and/or maintaining riparian communities and how hydrogeomorphic setting may influence riparian response. Specifically, I compared riparian herbaceous plant communities between the effluent-dominated, shallow-groundwater upper Santa Cruz, the effluent-dominated, deep-groundwater lower Santa Cruz, and a non-effluent control, the San Pedro River (Arizona, USA). Richness, cover, and community composition were assessed along longitudinal gradients of water and nutrient availability (surface flow permanence, distance from the point of discharge) and lateral gradients across the floodplain (distance from channel). I found that plant community composition shifted toward more nitrophilic species, such as *Conium maculatum* and *Polygonum lapathifolium*, and mean plant heights were at least two times greater at the perennial sites along the effluent-dominated reaches, indicating that both surface flow and water quality influence streamside patterns. I also found that hydrogeomorphic setting affects vegetation response to effluent discharge both laterally and longitudinally. Both effluent-dominated reaches maintained wetland plants for approximately 40 km downstream of respective discharge points, despite the fact that in the deep groundwater system, three times the volume of effluent is released. Lateral patterns showed that herbaceous cover and richness declined considerably outside of the first 10 meters of floodplain, and community composition abruptly shifted toward more xerophytic species, particularly in the deep-groundwater lower Santa Cruz.Overall, we conclude that effluent is a suitable option for maintaining environmental flows for near-channel riparian habitat in arid and semi-arid regions, and is more successful in sustaining floodplain vegetation in systems with shallow aquifers.

INTRODUCTION

The structure and dynamics of riparian ecosystems are the result of a suite of abiotic and biotic processes functioning at multiple spatial and temporal scales (Naiman *et al.*, 2005). In river floodplains, distribution patterns of overlapping plant communities characterized by different suites of species arise from gradients of resource availability and disturbance from the active channel to the uplands (Patten *et al.*, 1998; Hupp & Osterkamp, 1996; Marti *et al.*, 2000). Many of these patterns are due to key subsurface linkages between the stream channel, the parafluvial zone (the area of the active channel not covered by water), and the riparian zone via vertical, longitudinal, and lateral water movement (Dahm *et al.*, 1998; Illhardt *et al.*, 2000).

Rivers in arid and semi-arid regions can be differentiated from more mesic systems in that they function under intrinsic properties of water scarcity and associated hydrologic variability (Kingsford, 2006). In these regions, the hydrological regime exerts strong control on the biota with groundwater playing a key role in the hydrology-vegetation linkage by providing a sub-surface water source and contributing to the stream base flow (Katz *et al.*, 2009). Thus, riparian plant communities are especially sensitive to fluctuations in subsurface water availability. Perennial streamflow is associated with high plant cover and species richness; abundance, survivorship and productivity of many riparian plants is greater on floodplains underlain by shallow, stable water tables. (Stromberg *et al.*, 1996; Tabacchi *et al.*, 1996; Meyer *et al.*, 1999; Bagstad *et al.*, 2005; Lite and Stromberg, 2005). As streamflow becomes increasingly intermittent, herbaceous plant cover and species richness decline along the low-flow channel and across the floodplain (Lite *et al.*, 2005; Doody and Overton, 2009; Stromberg *et al.,* 2009).

In addition to inherent water scarcity and hydrologic variability, riverine ecosystems in the southwestern United States have been increasingly subjected to changes in flow conditions from agricultural pressures and urban development. These shifting baseline conditions, combined with episodic drought, have led to the drying of river reaches that were once perennial and a decline in the extent of riparian habitat from historical coverage (Brinson *et al.*, 1981; Segelquist *et al.*, 1993; Busch and Smith, 1995; Logan, 2002; Malmqvist and Rundle, 2002; Lite and Stromberg, 2005; Webb and Leake, 2006). Paradoxically, while development and consumption patterns in urbanized regions have impacted groundwater resources available to riparian ecosystems, these patterns also produce treated wastewater, much of which historically has been discharged into nearby river channels. Treated wastewater, or effluent, has become an increasingly important component of the freshwater landscape, particularly in more water-limited regions.

Treated wastewater is a potential water resource for the restoration and maintenance of riparian systems. However, numerous ecohydrological issues surround the influence of treated wastewater on river systems and their associated riparian plant communities. The introduction of treated wastewater into a stream can alter stream flow sufficiently to change the composition of the riparian community (Marler *et al.*, 2001; Brooks *et al.*, 2006). Increased nutrient levels in treated wastewater may bolster vegetation growth but can also lead to changes in plant species composition and dominance, leading to a reduction in species richness (Marler *et al.*, 2001; Craine *et al.,* 2002; Mathewson *et al.,* 2003; Verhoeven *et al.,* 2006). The hydrogeomorphic setting into which the effluent is released dictates the degree to which effluent discharge can restore vegetation within the multiple zones that comprise a riparian corridor, but this has yet to be studied.

Ensuring that treated wastewater contributes to, rather than degrades, riparian function hinges on an understanding of riparian plant community response to hydrological dynamics and water quality impacts in various hydrogeomorphic settings. In Arizona, treated municipal wastewater is often released into ephemeral channels with deep water tables, with some also released into intermittent or perennials streams. However, few studies have investigated how riparian vegetation response to the discharge of treated wastewater differs given underlying hydrology. We focused on an effluent-dominated waterway that spans two hydrological settings (deep groundwater disconnected from the stream flow, and shallow groundwater hydraulically connected to the stream flow) as our study river and a non-effluent control in the semi-arid southwestern United States to examine longitudinal and lateral patterns of herbaceous plant community response in the riparian zone. Our objectives were to increase our understanding of the ecological effects of the continuous release of treated wastewater by answering the following questions:

1. How does the riparian plant community in an effluent-dominated waterway vary longitudinally from the point of discharge given depth to groundwater, canopy cover and stream flow permanence?
2. How do riparian plant communities along the low-flow channel in effluent dominated waterways differ from non-effluent rivers in the southwestern United States with respect to composition, cover and richness?
3. How do composition, cover and richness in an effluent-dominated waterway vary laterally across the floodplain in relation to distance from channel, and do these zonal patterns differ from that in control streams?

We expected the following: (1) herbaceous riparian vegetation along effluent-dominated reaches would have greater cover, height, and abundance of nitrophilic species (but lower species richness) compared to perennial control reaches, due to the combination of perennial base flow input and elevated nutrients. (2) Herbaceous species richness and cover would decline within the effluent dominated river reaches with increasing distance from the point of discharge, and composition would shift toward more xerophytic species with increasing downstream distance and flow intermittency. (3) Across the riparian corridor in all stream types, species richness and cover would be highest within the near channel zone, with these traits declining most sharply with distance from the channel for the effluent-dominated reach in the deep-groundwater basin. Ultimately, our objective is to provide scientific evidence regarding potential outcomes of releasing treated wastewater into waterways with different hydrogeomorphic settings, so as to inform the restoration or maintenance riparian ecosystems in arid and semi-arid regions.

METHODS

Study Design

Our basic study design compared herbaceous riparian plant communities between an effluent-dominated riparian ecosystem with a shallow water table (Upper Santa Cruz reach), an effluent-dominated riparian ecosystem with a deep water table (Lower Santa Cruz reach), and a non-effluent control. Further, we examined plant community patterns with distance downstream from effluent outfall points (longitudinal analysis) and contrast zonal patterns among river types (lateral analysis).

Twelve study sites were selected along the Santa Cruz River in southern Arizona. In the upper Santa Cruz basin, two sites located five and ten kilometers upstream of the Nogales International Wastewater Treatment Plant (NIWWTP) provided non-effluent controls. Five effluent-dominated sites were situated within a 55-kilometer reach downstream from the point of discharge of the NIWWTP to capture changing flow conditions. Similarly, five sites were established along a 60-kilometer reach in the lower Santa Cruz to capture a gradient of flow intermittency downstream from the Roger and Ina Roads Wastewater Treatment Facilities. Nine sites were located along the San Pedro River, a less urbanized, non-effluent control river; three of these had perennial flow and six had intermittent or ephemeral flow (Figure 22; Table XII).

Study Area: effluent-dominated Santa Cruz River

The Santa Cruz River originates in the San Rafael Valley, part of the Madrean Archipelago ecoregion, an area characterized by basins and ranges, with medium to high relief spanning from 1000 to 1500 meters characterized by fault-block mountains separated by valley fill alluvium (AWWQRP, 2002). The river initially flows south and continues into Mexico following a 50-kilometer loop in which it turns northward and re-enters Arizona approximately eight kilometers east of Nogales. From the international border, the Santa Cruz River continues northward for 170 kilometers to the confluence of the Gila River (ADWR, 1999a; Figure 22). Historically, flow was perennial from its headwaters to near the town of Tubac, Arizona, approximately 65 kilometers north of the U.S./Mexico border. The river downstream of Tubac to the Gila River was characterized by intermittent and ephemeral reaches (Tellman *et al.*, 1997). Today the portion of the river that flows north in the U.S. can be divided into two effluent-dominated reaches, the upper and lower Santa Cruz River.

In the upper Santa Cruz reach, flow becomes perennial near the town of Rio Rico, approximately 21 kilometers north of the U.S./Mexico border, where treated wastewater is discharged from the NIWWTP into Nogales Wash immediately upstream from its confluence with the Santa Cruz River. The Santa Cruz River at the NIWWTP drains an area of approximately 1400 square kilometers, with approximately 900 square kilometers in Mexico (AWWQRP, 2002). The NIWWTP treats wastewater from Nogales, Arizona and surrounding communities, as well as wastewater from Nogales, Sonora. Release of treated wastewater into the upper Santa Cruz River began in 1951, and in 1972 the facility was upgraded and renamed the Nogales International Wastewater Treatment Plant (IBWC, 2005). In 1992 major upgrades to the treatment plant were completed, giving it a capacity of 17.2 million gallons per day (MGD) (AWWQRP, 2002). Technology upgrades were completed in 2009, leading to increased removal of nitrogen compounds and improvement of overall quality of the discharged water (IBWC, 2010). The effluent-dominated perennial flow in the Santa Cruz River extends from the NIWWTP approximately 50 kilometers north beyond Tubac, Arizona, where flow intermittency increases with increasing distance from the point of effluent release.

The lower Santa Cruz River begins in the Tucson metropolitan region, and extends downstream to the confluence with the Gila River. This floodplain experienced a complex alluvial history culminating in a major cut and fill cycle between 500 and 300 years ago (Rosen, 2005). Prior to the onset of European settlement, the lower Santa Cruz River was a shallow stream occupying a broad, flat floodplain covered with mature mesquite forests and cottonwood trees (Johnson and Haight, 1981). Flows were historically variable and highly dependent on season. By the early 20th century, flows were becoming increasingly intermittent in many areas due to groundwater pumping for agricultural practice and urban development. Growth patterns have continued to lower the water table to over 50 meters below the surface (AWWQRP, 2004).

Today, the lower Santa Cruz River has perennial flow at present only because of discharges of treated wastewater from the Roger Road Wastewater Treatment Plant (WWTP) and Ina Road Wastewater Reclamation Facility (WRF). More than 50 million gallons per day (mgd) of treated wastewater is discharged into the river channel, creating base flows for nearly 50 kilometers that support a narrow band of *Salix*-dominated forest, set within a relatively dry floodplain. In the urbanized landscape, the floodplain is narrow and incised and flood scour tends to be severe (PCFD, 2005). Further downstream where Avra Valley opens into the Santa Cruz Flats near the Pinal County line the floodplain become less constricted and flow becomes increasingly intermittent. However, in this area, agricultural run-of combined with treated wastewater to support a central riparian corridor with marshy grounds and ponds and a mesquite bosque (forest).

Study Area: non-effluent San Pedro River

The San Pedro River is an undammed river that flows northward from its headwaters in Sonora, Mexico, to its confluence with the Gila River near Winkelman, Arizona (Figure 22). Based on geomorphic differences, the river is divided into two basins within the San Pedro River watershed (Tuan, 1962). The upper basin extends from its headwaters (elevation 1500 m) to a geologic constriction known as the Narrows (elevation 1000 m) and the lower basin extends from the Narrows to the confluence with the Gila River (elevation 580 m).

The San Pedro River is an interrupted perennial river; perennial reaches, with year-round surface flow, are interspersed with intermittent reaches (dry for part of year) and ephemeral reaches (dry for most of the year) (Katz *et al.*, 2009). Groundwater pumping for agriculture and mining activities have decreased surface water and groundwater levels leading to an increase in flow intermittency in some parts of the river. In some areas, water availability in the riparian zone has fallen below threshold levels needed to sustain *Populus*-*Salix* forests and emergent wetlands (Lite and Stromberg, 2005; Stromberg *et al.*, 2005). In these reaches, stream channels are wide and dry, supporting little herbaceous vegetation with *Tamarix* shrublands as the predominant woody cover.

Climate and Hydrology Data

Precipitation in the Santa Cruz and San Pedro study areas is bimodal, with convective thunderstorms creating a summer monsoon rains and Pacific frontal storms providing precipitation in winter. In the upper Santa Cruz reach, mean annual flow at the USGS Nogales gage (USGS #09480500) for years 2007 and 2008 was 0.195 m^3s^{-1} and 0.087 m^3s^{-1} respectively. The Nogales gage is located approximately 15 kilometers upstream of NIWWTP, outside of the effluent influence. Within the effluent-dominated reach of the upper Santa Cruz River, mean annual flow at the Tubac gage (USGS #09481740) for study years 2007 and 2008 was 0.87 m^3s^{-1} and 0.78 m^3s^{-1} respectively. For the effluent-dominated lower Santa Cruz River, mean annual flow at Cortaro gage (USGS # 09486500) measured 2.27 m^3s^{-1} and 2.08 m^3s^{-1} for study years 2007 and 2008. This gage is located approximately 10 kilometers downstream from Roger Road outfall (Table XXIII).

In the upper basin of the San Pedro River, mean annual flow at Charleston (USGS #09471000) for study years 2007 and 2008 was 1.01 m^3s^{-1} and 0.97 m^3s^{-1} respectively. The gage near Redington Bridge (USGS # 09472050) measured mean annual flow in 2007 and 2008 as 0.54 m^3s^{-1} and 0.69 m^3s^{-1} for the lower San Pedro basin. For both rivers, stream flow varies widely among years (Figure XXIII).

Field sampling

Streamside and floodplain herbaceous vegetation were sampled four times: early summer dry season (late May–early June) and late summer wet season (late August–early September) of 2007 and 2008. In the Sonoran and Chihuahuan Deserts, May - June is usually a period with low rainfall and low stream flow rates. During this time, herbaceous riparian vegetation patterns most strongly reflect base flows and groundwater hydrology, as opposed to being influenced by precipitation or flood pulses (Lite *et al.*, 2005).

The streamside zone was defined as the zone of direct influence of the low-flow stream channel, including channel bars, benches and stream banks, and inclusive of areas with shallow water (up to 10 cm) and emergent aquatic vegetation. At each site, data were collected at three streamside locations separated by a distance of 100 m. Six 1-m^2 herbaceous plots were randomly located within two meters of the stream edge along a 20-meter span at each transect (18 total per site). Percent cover of each herbaceous species was estimated using modified Braun-Blanquet cover classes (Hurst & Allen, 2007). Percent canopy cover was also recorded at each plot. Data were also collected on height of the tallest herbaceous plant per plot.

Floodplain vegetation was sampled along two transects, 100 meters apart, per site. Each transect was perpendicular to the primary channel, and extended from the thalweg (channel low point) to closed *Prosopis velutina* forest or *Sporobolus wrightii* grassland on the terrace or, in some cases, anthropogenic land use. Transects encompassed the zone vegetated by forests of *Populus fremontii - Salix gooddingii* as well as shrublands of *Tamarix ramosissima*, *Baccharis salicifolia*, *Baccharis sarothroides*, *Hymenoclea monogyra*, *Ericameria nauseousa,* and young *Prosopis velutina*. Floodplain width, thus transect length, ranged from 65 to 215 m on the Santa Cruz River (mean of 123 m) on the Santa Cruz River and from 71 to 550 m (mean of 305 m) on the San Pedro River.

Herbaceous plots were located in a stratified random fashion, with two 1-m^2 plots embedded within larger woody quadrats within identified patch types. Vegetation patches along transects were classified using a rule-based system defined by dominant woody species, canopy cover class, tree size class, and fluvial geomorphic surface. Herbaceous vegetation measurements followed the same protocol as streamside vegetation, using modified Braun-Blanquet cover classes (Hurst & Allen 2007). If patches along transects were wider than 25 m, we added two randomly sampled herbaceous plots for each additional 25 m of that patch.

Plants were identified to species, when possible. Nomenclature follows Kearney and Peebles (1960) and recent taxonomic treatments published as part of the Vascular Plants of Arizona project (e.g. Wilken and Porter, 2005). Voucher specimens were collected and placed in the Arizona State University herbarium. Plant species were classified according to water availability needs using wetland indicator scores (WIS) for the southwest (Region 7; USDA-NRCS, 2007). These scores signify the probability that a species will occur in a wetland environment. For our study, obligate and facultative wetland species were grouped as hydric, facultative and facultative upland as mesic, and non-wetland as xeric. Herbaceous species were also classified based on lifespan and nativity to North America (http://plants.usda.gov/). Annuals included species with predominantly annual or biennial life spans; perennials were those that live three or more years. Ellenberg N (nitrogen) scores (Ellenberg, 1979) were assigned when possible, and modified to an average for genus if specific-species information was not available.

Data analysis- longitudinal patterns

Pearson correlation analysis was used to determine whether streamside vegetation metrics - herbaceous cover, species richness, plant height, canopy cover, weighted average wetland indicator score and weighted average Ellenberg N score - varied with distance downstream from effluent outfall points for the sample of 5 sites on the Upper Santa Cruz and 5 sites on the Lower Santa Cruz. Analyses were conducted for each of the 4 seasonal data sets, using plot averages per site (n=18). To account not only for distance from effluent effects but also for canopy cover differences among sites, multiple regression analyses were conducted on this same set of vegetation metrics with distance from outfall and canopy cover as the independent variables. To visually compare plant diversity among sites and seasons, species accumulation curves were generated from random permutations of the data (Gotelli & Colwell, 2001) using expected richness per plot via Sobs (Mao Tau) in Estimate S 8.2.0 (Colwell*et al.*, 2004). One set of curves was generated from the 18, 1-m^2herbaceous streamside plots across four sampling seasons at all 21 sites (12 on Santa Cruz River; 9 on San Pedro; n = 378 plots annually, except for pre-monsoon 2007 where n = 306).

Data analysis – comparison among river types

To compare richness, abundance, and composition of streamside herbaceous communities among river settings (upper Santa Cruz, lower Santa Cruz, San Pedro), two-factor analysis of variance was conducted using the General Linear Models procedure in PASW 18. This analysis was restricted to comparison of perennial sites (n=3 for each river setting), using elevation and river setting as independent variables. Analysis of variance also was conducted in SAS v. 9 (SAS Institute Incorporated, 2007) for all sites using river setting and flow permanence as independent variables on the 2008 data only. For this analysis, flow permanence was categorized into three groups: 0-30% flow, 31-99% flow, and 100% flow. Differences were highlighted using Tukey HSD post-hoc multiple comparisons. Statistical relations were considered significant at $p \leq 0.05$, and variables were transformed as necessary to meet assumptions for normality and equality of variance.

Data analysis – lateral patterns

Similar to the longitudinal analyses, another set of species curves was generated for floodplains, using data from the 1-m^2herbaceous plots located in the floodplain, using expected richness per plot via Sobs (Mao Tau) in Estimate S 8.2.0 (Colwell*et al.*, 2004). For these curves the number of plots per site varied depending on floodplain width.

To assess changes in herbaceous plant communities with lateral distance from the channel, three zones were established: the streamside zone (0-2 meters of channel), near floodplain (2-10 meters) and far floodplain zone (10+ meters). The number of plots per zone varied among sites with the minimum number being 8. A one-way ANOVA for each site comparing richness, abundance, and other community metrics among zones was conducted in PASW 18. We used pre-monsoon 2008 site data (Upper Santa Cruz, n = 7; Lower Santa Cruz, n = 5; San Pedro, n = 9 sites) to emphasize the influence of effluent flows.

RESULTS

Longitudinal patterns: changes in streamside plant communities with distance downstream from effluent-discharge points

*Upper Santa Cruz River (E_{SG}).*Herbaceous species richness, cover, plant height, canopy cover, and nitrogen (N) scores were all negatively correlated with distance from the point of treated wastewater release in the shallow-groundwater upper Santa Cruz River, with some variance in strength of correlations among seasons (Figures 24&25 Table XIV). For species richness, the decline in streamside species richness with distance was significant across all sampling seasons, with lowest richness at the two sites that had the least effluent influence and thus intermittent flow (Table XIV). Species accumulation curves also revealed a pattern of decline in streamside species numbers with increasing distance from the point of discharge (Figure 26).

Streamside canopy cover, which decreased with increasing distance, interacted with effluent flow to influence understory vegetation (Table XV). Herbaceous cover had high negative correlations with distance in all seasons except one of the two monsoon samplings (Table XIV). Analysis with multiple regression showed that canopy cover had an overriding effect on herbaceous cover during the monsoon season, while distance was the variable most strongly linked to cover for the pre-monsoon baseflow season (Table XV). Sites with the highest streamside canopy tended to have less herbaceous cover (and lower species richness and shorter understory plants) than those sites in which sunlight could reach the understory.

Streamside plant community composition shifted with downstream distance. Species with higher nitrogen affinity, such as *Conium maculatum* and

Polygonum lapathifolium, were found at perennial flow sites close to the point of treated wastewater introduction. Wetland indicator scores increased downstream, in tandem with increasing intermittency of flow. Species common at perennial sites were obligate and facultative wetland species, such as *Nasturtium officinale*, *Veronica anagallis-aquatica*, *Hydrocotyle verticillata, Conium maculatum* and *Polygonum lapathifolium,* and shifted toward mesic and upland species such as *Cynodon dactylon, Schismus barbatus, Amaranthus palmeri, and Salsola tragus* at the drier sites.

Lower Santa Cruz River (E_{DG}). Species richness, herbaceous cover, plant height, and nitrogen score of the streamside plant community were also negatively correlated with distance from the point of treated wastewater release in the lower Santa Cruz River (Figures 24 & 25; Table XIV). Declines in streamside species richness and cover occurred in both the wet and dry seasons (Table XIV). In contrast to the E_{SG}reach, streamside canopy patterns in this reach increased with increasing distance downstream likely owing to the input from agricultural inflows in the downstream reaches. Multiple regression of distance combined with canopy cover indicated effects of both of these independent variables on streamside herbaceous cover, richness, wetland indicator score, and N score (Table XV).

Similar to the upper Santa Cruz, wetland indicator scores decreased significantly with increasing distance, reflecting less effluent influence and increased flow intermittency. Close to the point of effluent introduction, obligate and facultative species such as *Typha domingensis, Veronica anagallis-aquatica and Polygonum lapathifolium* were common*,* and further downstream composition shifted toward species such as *Cynodon dactylon* and *Amaranthus* *palmeri.* N scores were highest nearest the effluent outfall, with dominance by high-N species including *Typha domingensis, Polygonum lapathifolium, Setaria grisebachii,* and *Echinochloa sp.*

Comparing streamside plant communities between effluent and non-effluent rivers

Species richness. Focused analysis on the perennial sites indicated that mean streamside richness per 1-m^2 plot was higher in the E_{SG} and E_{DG} reaches than on the control during the post-monsoon season (Figure 28B; Table XVI). Values did not differ among river types during the pre-monsoon season. Pre-monsoon plots averaged 3.2 and 3.0 and post-monsoon 3.1 and 3.0 species per m^2 in the E_{SG} and E_{DG} reaches respectively. Perennial sites on the control river had an average of 2.4 and 2.1 species per m^2.

Multi-site analysis (Table XVII) indicated that plot richness was related to stream flow permanence, but only for the pre-monsoon season. Highest streamside species numbers, overall, occurred at intermittent sites of the control following the monsoon season (Figures 26 & 27).

Pre- and post-monsoon values for cumulative streamside herbaceous richness averaged 10 and 11 species per site in E_{SG} and 11 and 14 species per site in E_{DG}. Control numbers were slightly lower with 9 and 8 species. For the rivers as a whole, there were a combined total of 82 species in the streamside zone of the twelve effluent-dominated Santa Cruz River sites and 84 species in the nine sites of the control river (Appendix III).

Herbaceous cover. Surface flow permanence had significant effects on herbaceous cover although river setting did not (Table XVII), with values highest at the perennial flow sites for all three rivers. Post-hoc Tukey tests indicated that river setting also had an effect, with cover during the pre-monsoon season significantly higher in E_{SG} and E_{DG} reaches than in the control (Figures 29A and 30A; Table XVII). For post-monsoon samples, herbaceous cover also was highest in the $E_{DG.}$ Restricting the analysis to the perennial sites only (n = 3, each river type) confirmed that river setting had a significant effect on herbaceous cover ($F_{(2,4)} = 9.424$, $p < 0.05$) independent of flow, with cover higher on the effluent-dominated reaches (Figure 28). This river setting effect at the perennial sites likely reflects interactions with canopy cover, in that herbaceous cover was highest in the streamside zone of E_{DG}, which had lower canopy density than did the perennial sites of the E_{SG} and control (Figure 28).

Streamside canopy cover. Canopy cover was highest on the control river and lowest in E_{DG} (Figure 28; Table XVI). This between-river pattern is most likely a result of differences in stream hydrology rather than in nutrient effects. Neither river setting nor elevation had significant effects on canopy cover, whereas surface flow permanence had significant effects on canopy cover with denser canopy at wetter sites (Figures 28 & 29; Table XVII)

Plant height. Plant heights were significantly greater at the perennial sites in the effluent-dominated system compared to the control (Table XVI). On average, tallest plants were in the E_{DG} reach, averaging 119 cm and 96 cm in the pre- and post-monsoon seasons. In the E_{SG} reach, plant height averaged 76 cm and 65 cm in pre- and post-monsoon samples. Plant heights in the control river were significantly lower with 36 and 21 cm for pre- and post-monsoon seasons, respectively (Figure 28D). Flow permanence was an important influence on plant height, but river type retained a strong significant effect after accounting for flow (Figures 29D & 30D).

Composition. The comparison of perennial sites for all three river settings did not reveal any significant differences in wetland indicator scores in either pre- or post-monsoon season (Figure 28E; Table XVI). Flow permanence had a significant effect on wetland indicator scores, but river setting did not (Figures 29E &30E; Table XVII). N scores were more revealing regarding compositional differences at perennial sites based on river setting (Table XVI). N scores were significantly different between all three river settings for pre-monsoon samples when effluent influence is not dampened by seasonal precipitation (Figure 28F). River setting and flow permanence both yielded significant differences in N score, with the highest N scores occurring at perennial flow sites of both the E_{SG} and E_{DG} reaches (Table XVII). N scores in the streamside perennial sites averaged of 6.8 and 7.1 in the E_{SG} and E_{DG} reaches, and 5.5 on the control. Among flow categories, differences in N scores were most pronounced for the perennial flow sites (Figures 29F & 30F).

Ordination analysis patterns for pre-monsoon 2008 data yielded a 2-D solution related to flow permanence and river type (final stress = 11.397, final instability = 0.0156; Figure 31A) and accounted for 96% of the variability in the data set. Axis 1 was positively correlated with river setting (r = 0.506) and flow permanence (r = 0.165). Axis 2 was most significantly related to flow permanence (r = 0.739) and also positively correlated with river setting (r = 0.316) and flow permanence (r = 0.739). Post-monsoon data also yielded a 2-D solution (final stress = 10.642, final instability < 0.0001; Figure 31B) and accounted for 84% of the variability in the data set. Axis 1 was positively correlated with river setting (r = 0.482) and flow permanence (r = 0.262). Axis 2 was negatively correlated with river setting (r = -0.196) and flow permanence (r = -0.400).

Lateral patterns: changes in herbaceous plant communities across floodplains of effluent-dominated and non-effluent rivers

Herbaceous cover. On the control river, herbaceous cover differences by zone varied strongly by site, reflecting site hydrology and canopy cover heterogeneity. For perennial sites, cover in the streamside zone was significantly lower than in near or far floodplain zones, likely due to high density of canopy cover along the channel (Table XIX; Figure 36). Most of the intermittent and ephemeral sites, in contrast, had significantly higher cover in the streamside zone compared to zones further from the channel (Table XVI, Figure 37). On the effluent river, herbaceous cover declined more frequently with increasing distance from the perennial flow channel. The patterns were strongest in the deep-groundwater lower Santa Cruz with less canopy influence. In the E_{DG} reach, herbaceous cover declined significantly with increasing distance across the floodplain at all 5 sites (Table XVIII; Figure 35). In the E_{SG} reach, however, a dense riparian forest influenced herbaceous cover at the sites closest to the treatment facility. At sites 15, 25, 35, and 45 km downstream, however, cover declined significantly from the streamside to far floodplain. The site 55 km downstream had very little effluent input and herbaceous cover in the floodplain did not change significantly with distance from the low flow channel (Table XVIII; Figure 34).

Herbaceous species quadrat richness. Lateral patterns of herbaceous species richness on the control river varied by flow permanence (Figures 36 & 37; Table XIX). Most perennial and intermittent sites had higher pre-monsoon species richness in the near floodplain (2-10 m) zone and far floodplain compared to the streamside (Figure 36). Of the two ephemeral sites, one (Narrows) did not have significant differences across zones and the other had high richness in the floodplain. Additionally, there were no significant differences in species richness across floodplain zones at the non-effluent sites control sites upstream of NIWWTP in the E_{SG} reach (Figure 34; Table XVIII).

In contrast to the control sites, there was a significant decline in herbaceous species richness in both effluent-dominated reaches with increasing distance from the perennial flow channel, particularly in the deep-groundwater reach. Species richness in the E_{DG} and E_{SG} reaches declined significantly with distance from channel for nearly all the sites (Table XVIII; Figures 34 & 35). Species richness in both reaches was highest in streamside zones, and declined significantly within 10 meters of the low flow channel in the E_{DG} reach in particular. Average species/m^2 for combined pre-monsoon data was 2.6 in the near floodplain zone (2 - 10 m from channel) and 1.7 in the far floodplain zone (10+ m) in the E_{SG}. Post-monsoon data averaged 2.5 species/m^2 and 1.8 species/m^2 for the near and far zones respectively. Sites along the E_{DG} reach averaged 2.8 and 1.4 species/m^2 and post-monsoon data averaged 2.8 and 1.5 species/m^2 in the near and far floodplain zones respectively. Sites along the control river averaged 2.9 and 2.2 species/m^2 (pre-monsoon) and 3.0 and 2.6 species/m^2 (post monsoon) in the near and far floodplain zones.

Species accumulation curves showed that species numbers were significantly higher in the floodplains of the control river and seasonal variation was more evident in floodplain patterns, with more species occurring in post-monsoon seasons (Figures 32 & 33). Numbers of species were similar in the E_{SG}

and E_{DG} reaches, but both reaches were significantly lower than the control (Figures 32 & 33). Total numbers of herbaceous species in the floodplains of the E_{SG}, E_{DG} and control varied based on surface flow permanence and floodplain width.

Canopy cover. On the control river, lateral patterns for canopy cover varied with site hydrology. Two of the three perennial sites on the control had significant differences across floodplain zones, with canopy decreasing with distance from the channel (Table XIX; Figure 36). Intermittent site trends for canopy cover were more variable (Figure 37). The two ephemeral sites (Narrows, HE3) had highest canopy cover in the far floodplain zone, which was dominated by *Prosopis velutina and Tamarix ramosissima.* There were no significant differences between zones for the two upstream non-effluent sites on the Santa Cruz.

Lateral patterns for canopy cover also varied with site hydrology in the E_{SG} reach. In the perennial sites of E_{SG} nearest to the point of effluent discharge, *Populus*-dominated canopy cover was highest in the streamside and near floodplain zones and declined further out in floodplains, similar to patterns at the perennial controls (Figure 34). As flow intermittency and downstream distance increased, however, there were no significant differences across the floodplain (in contrast to the control), largely because tree species were no longer present in any zone.

In the E_{DG} reach, perennial sites closest to the point of discharge did not have significant differences across zones. For sites farther downstream, canopy (dominated by *Salix goodinggii)* increased in the streamside and near floodplain zones but was not maintained in the far floodplain (Table XVIII; Figure 34).

Composition. At the control river, wetland indicator scores were lowest in the streamside and near floodplain zones, and were higher in the far floodplain. Differences among zones were significant for all three perennial sites and for the four of the six intermittent and ephemeral sites (Table XIX; Table XVIII; Figures 36 & 37). In the two control sites on the Santa Cruz River upstream of the NIWWTP, there were no significant differences across floodplain zones in wetland indicator (Figure 34). The patterns for wetland indicator scores in the two effluent-dominated reaches were similar to those on the San Pedro control, in that values increased (i.e. became drier) with increasing distance from the low flow channel and decreasing water availability (Table XVIII; Figure 34 & 35). The magnitude of change across zones was most pronounced for perennial sites in the E_{DG} reach, with WIS scores shifting from an average of 1.9 in the streamside zone to 4.2 in the far floodplain. Differences in WIS between zones were diminished with distance downstream (and increasing intermittency) because very few wetland species were supported in the streamside zone at these sites.

At the control river, nitrogen scores tended to be lowest further away from the low flow channel, but patterns were not as strong as for the effluent reaches. Differences for N score at the control river were significant across zones for all three perennial sites (Table XIX; Figure 36), but did not differ among zones at the six intermittent or ephemeral sites (Figure 37) nor at the two control sites on the Santa Cruz River upstream of the NIWWTP (Figure 34). In the effluent-dominated reaches, in contrast, N score declined significantly from the streamside to far floodplain at all but one site (Table XVIII; Figure 34 & 35).

DISCUSSION

Our investigation of streamside and floodplain herbaceous plant communities revealed differences in community structure between effluent-dominated and non-effluent rivers in the semi-arid southwestern United States. We were able to identify four factors that significantly influenced herbaceous plant community patterns and development along effluent dominated rivers. Our research verified water quality and surface flow hydrology as two important drivers shaping riparian plant community diversity, abundance, and composition. Depth to groundwater also emerged as an influential variable as distinct zonal patterns emerged in herbaceous cover, species richness and composition with increasing distance from the perennial effluent particularly in reaches with greater depth the groundwater. Lastly, canopy cover also affected streamside community metrics, particularly at perennial sites that supported significant *Populus*-*Salix* forest.

Nutrient influences

Effluent-dominated streams have unique water quality characteristics because treated wastewater is typically high in ammonia, nitrate, and phosphate (Grimm & Fisher, 1986b; Marler *et al*, 2001; Brooks *et al.*, 2006). Flows in the Santa Cruz River have been supplemented by treated wastewater for more than 40 years, and portions are listed as an impaired waterbody (USEPA, 2007) for ammonia, nitrogen, phosphorous and 7 other compounds (ADEQ, 2008). The elevated nutrients in effluent discharge are a concern for many treatment plant managers (AWWQRP, 2002) and numerous studies have shown accelerated growth or biomass production with increasing nitrogen concentration (Kowalik & Randerson, 1994; Karpsicak *et al.*, 1996; Hubbard *et al.*, 1999; Marler *et al.*, 2001). Our results are consistent with others in that we found average streamside herbaceous plant heights along the effluent-dominated reaches to be at least two times greater than those on the non-effluent control. We also documented compositional shifts on the Santa Cruz River toward nitrophilic species that can tolerate and thrive in elevated nutrients. Greater plant height in the effluent-dominated system (and thus presumably greater biomass) largely reflected these compositional shifts, with nitrophilic species (such as *Conium maculatum* and *Polygonum lapathifolium*) tending to grow larger than non-nitrophiles.

Upstream of the NIWWTP, total Kjeldahl nitrogen (TKN) and total phosphorus in 1993 were below 1.0 mg L^{-1}, similar to findings for other natural Arizona streams (Grimm & Fisher, 1986b; Stromberg *et al.*, 1993). Since that time, flow upstream of NIWWTP has become increasingly intermittent due to extensive groundwater pumping and a period of drought. Downstream of the treatment facility, vegetation response to the pulse of nutrients and water released from the NIWWTP is substantial. Nutrient dynamics then change longitudinally downstream from the point of discharge (Patten *et al.*, 1998) as nutrients are utilized quickly by the aquatic and streamside communities (Schade *et al.*, 2005), resulting in declines in concentrations of nutrients with increasing distance from the discharge point (Patten *et al.*, 1998; Duran and Spencer, 2004). Our results indicated similar patterns as plant heights and dominance of nitrophiles also declined with increasing distance from the point of discharge. Finally, lateral zonation patterns showed that abundance of nitrophilic species was highest within the first two meters of the effluent-dominated reaches, but compositional shifts were still evident within the first ten meters of the effluent flows. Further out in the floodplain, outside of the immediate zone of effluent influence, herbaceous plant communities were not shifted toward plants with higher nitrogen affinities.

Surface flow influences

Riparian plant community distributions and patterns are often reflective of multiple environmental gradients (Stromberg et. al, 2009; Chessman & Royal, 2010) and in effluent-dominated systems, some gradients may be amplified (nutrients) while others are somewhat dampened (surface flow intermittency). Both study reaches are interrupted perennial rivers with effluent discharge influencing the extent of perennial base flow, and thereby influencing the vegetation. For both effluent-dominated reaches of the Santa Cruz River, sites with perennial flow closer to the point of effluent introduction supported higher herbaceous cover and species richness and had more wetland species compared to downstream sites outside of effluent influence. This is consistent with previous research which has shown that reliably wet habitats in arid environments support distinct groups of wetland species that do not occur in uplands (Stromberg *et al.* 2005; Rhazi *et al.*, 2009; Katz *et al.*, 2009). The two furthest downstream sites in the upper reach were consistently dry, and low species numbers and no wetland species reflected these environmental conditions. In the lower reach, species numbers remained consistently higher and wetland species persisted, largely due to greater effluent volumes and additional agricultural input further downstream. Finally, when comparing the effluent-dominated reaches with the control, streamside community composition and plant height differences were most significant at perennial sites.

Groundwater effects

Our study also reveals how hydrologic setting with respect to groundwater shapes the response of riparian plant communities to effluent discharge, particularly in floodplain zones. The upper Santa Cruz effluent-dominated reach had a shallow riparian water table whereas the effluent surface channel in the lower Santa Cruz reach was disconnected from the stream aquifer owing to historic depletion by groundwater pumping. Across the floodplains of the effluent-dominated system, species richness and herbaceous cover declined and there was a distinct shift toward more xerophytic species with increasing distance from the low flow channel. These shifts were especially evident in the deep-groundwater lower Santa Cruz reach, likely reflecting the xeroriparian nature of the lateral zones.

One key management question is how much riparian habitat can be sustained by effluent discharge and how hydrogeomorphic conditions may influence response. On both reaches of the Santa Cruz, the longitudinal extents of wetland plants along the stream channel were similar (40 km downstream from the NIWWTP when surface flows dissipate completely, 50 km downstream from Roger and Ina WWTPs, where flow is supplemented by agricultural runoff). This occurred despite the fact that the deep-groundwater lower Santa Cruz reach receives over 50 MGD of effluent flow while the shallow-groundwater upper reach receives approximately 17 MGD of effluent. Much of the effluent in the lower Santa Cruz reach likely infiltrates into the stream bed (Galyean, 1996), thereby reducing the water available to riparian plant communities, and indicating that underlying hydrology (depth to groundwater) is an also important in shaping longitudinal patterns.

Zonation patterns for abundance and community composition across the floodplain of the effluent-dominated reaches were much more pronounced than in the floodplain of the control river. In the non-effluent San Pedro River, herbaceous cover and species richness were highest at the intermittent sites, particularly in post-monsoon conditions. These patterns were consistent with previous research, which has found that intermittent sites may be most ideally suited for accumulating species-rich plant assemblages over time due to variability in hydrology and geomorphic heterogeneity (Berlow *et al.*, 2008; Katz *et al.*, in review).

Canopy effects

Effluent release indirectly affects streamside herbaceous patterns by influencing forest growth along the low-flow channel. Streamside forest canopy was associated with reduced herbaceous cover and species richness in the perennial-flow sites along the shallow-groundwater upper Santa Cruz and San Pedro Rivers. These sites had dense growth of broad-leaved trees along a relatively narrow active channel, in contrast to intermittent sites, which had less tree cover and deeper groundwater tables. Dense tree canopy may shape understory communities through various mechanisms including temperature moderation, shading, substrate stabilization, litter inputs, and uptake of nutrients (Follstad-Shah and Dahm, 2008; Katz *et al.*, 2009). These factors also create a more geomorphically stable environment than non-perennial reaches (Heffernan 2008), enhancing accumulation and retention of hydric seeds while also limiting opportunities for species turnover (Katz *et al.*, 2009). Thus, streamside herbaceous cover and species richness were higher in the lower Santa Cruz reach sites with perennial effluent influence and lower forest canopy, but declined significantly with increasing downstream distance and flow intermittency.

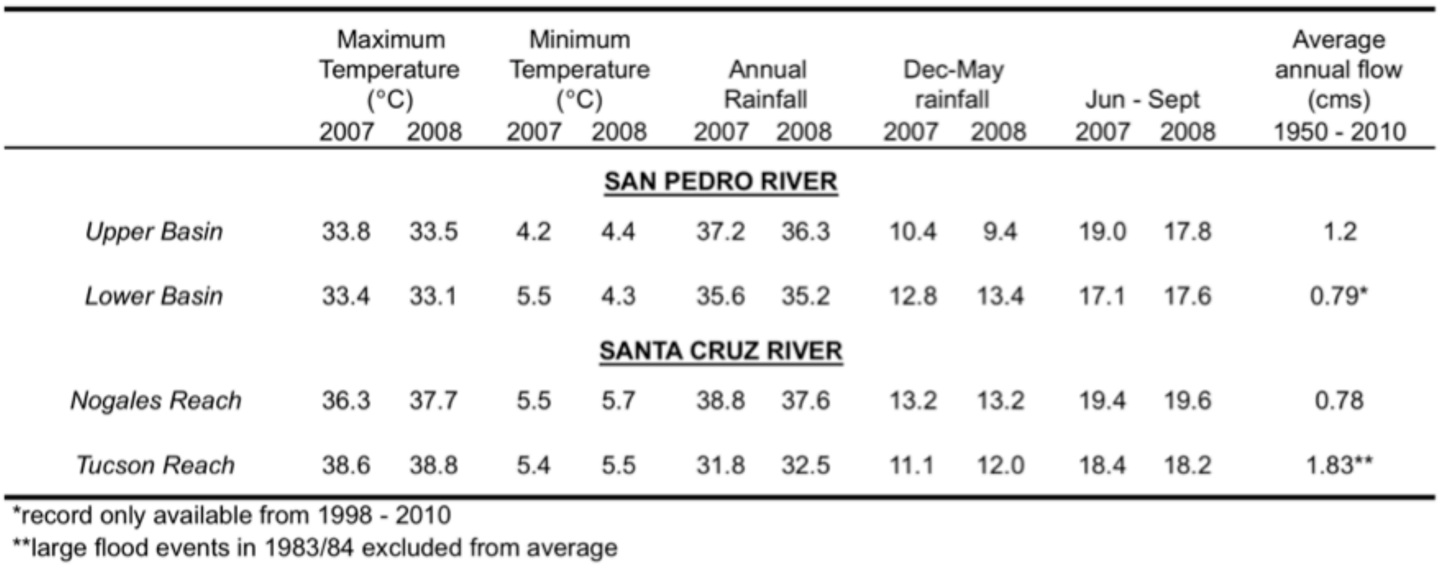
CONCLUSIONS

Management and maintenance of river systems in the southwestern United States is becoming increasingly complex due to human impacts, multiple and competing water needs, and climate variability. The use of effluent as a source of water for the environment raises important questions about the benefits and impacts of effluent on riparian structure and function, particularly in the context of drought, societal freshwater needs and environmental flows. The Santa Cruz River in southern Arizona has proven an ideal laboratory in which to study ecological dynamics of an effluent-dominated riparian system and begin developing tools for monitoring and managing other similar systems. Our research has shown that effluent-dominated systems have clear longitudinal patterns driven by the increase in water availability and nutrients. Previous studies have indicated that long-term water resource availability can mediate plant community response to short-term rain and flood events. For example, Stromberg *et al.* (2009) found that cumulative richness of streamside species through multiple seasons was higher at intermittent sites than at perennial sites because water limitation increased bare ground and allowed for greater turnover of annual species in response to short-term water pulses from rain and floods. The long-term, continual release of effluent sustains streamside herbaceous cover, but spatial and temporal dynamics are dampened, and diversity is affected as community composition shifts toward more nitrogen-tolerant species. From a management perspective, a threshold change in vegetation composition highlights the complex relationships between external factors (i.e., climate) and system-specific components (i.e., water quality). Ultimately, the current lack of understanding about systems receiving effluent underscores the growing need for suitable methods to evaluate ecological dynamics of these systems. Although some biotic and abiotic attributes varied between reaches, the overall picture shows structural and functional similarities in the riparian vegetative communities established on the control and effluent reaches.

Table XII. Study site information along the Santa Cruz and San Pedro Rivers

		SAN PEDRO RIVER *(Non-effluent control)*				
Site Name	Map Code	Flow Permanence	Elevation (m)		Latitude	Longitude
Lewis Springs	1	perennial	1230		31.555827	-110.139770
Fairbanks	2	intermittent	1166		31.719315	-110.192990
Narrows	3	intermittent	1006		32.135674	-110.289234
Three Links Farm #1	4	perennial	998		32.164181	-110.295619
Three Links Farm #3	5	intermittent	988		32.197852	-110.313022
Spirit Hollow Intermittent	6	intermittent	786		32.576149	-100.515918
Spirit Hollow Perennial	7	formerly perennial	783		32.533110	-110.519229
H&E #3	8	intermittent	689		32.773245	-110.674157
TNC Preserve P	9	perennial	604		32.930766	-110.743122
		SANTA CRUZ RIVER *(Effluent-dominated)*				
				Distance from Outfall (km)		
Santa Fe Ranch	10	intermittent	1092	-10	31.404300	-110.896519
Calabasas	11	intermittent	1070	-5	31.429878	-110.924696
		Nogales International Wastewater Treatment Facility				
Santa Gretudis	12	perennial	995	15	31.561632	-111.046291
Chavez Siding	13	perennial	960	25	31.645824	-111.047550
Amado	14	perennial	936	33	31.703670	-111.054035
Continental	15	intermittent	875	48	31.835892	-110.990138
Sahuarita	16	intermittent	825	60	31.959540	-110.963874
		Roger and Ina Roads Wastewater Treatment Facilities				
Ina	17	perennial	660	8	32.336229	-111.080780
Avra Valley	18	perennial	629	18	32.401843	-111.143707
Hardin	19	perennial	576	38	32.480063	-111.322608
Sasco	20	intermittent	549	48	32.544830	-111.406742
Wheeler	21	intermittent	539	58	32.577608	-111.467493

Table XIII. Climate and hydrology information for the upper and lower Santa Cruz and San Pedro Rivers.



	Maximum Temperature (°C)		Minimum Temperature (°C)		Annual Rainfall		Dec-May rainfall		Jun - Sept		Average annual flow (cms)
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008	1950 - 2010
					SAN PEDRO RIVER						
Upper Basin	33.8	33.5	4.2	4.4	37.2	36.3	10.4	9.4	19.0	17.8	1.2
Lower Basin	33.4	33.1	5.5	4.3	35.6	35.2	12.8	13.4	17.1	17.6	0.79*
					SANTA CRUZ RIVER						
Nogales Reach	36.3	37.7	5.5	5.7	38.8	37.6	13.2	13.2	19.4	19.6	0.78
Tucson Reach	38.6	38.8	5.4	5.5	31.8	32.5	11.1	12.0	18.4	18.2	1.83**

*record only available from 1998 - 2010

**large flood events in 1983/84 excluded from average

Table XIV. Pearson correlation (r values) relating distance from effluent outfall to traits of herbaceous streamside plant communities along the effluent-dominated Santa Cruz River. Values are shown for four sampling seasons. Bold values denote significance, alpha = 0.05, n = 5 (Upper Santa Cruz) and n=5 (Lower Santa Cruz).

	Upper Santa Cruz River							
	Pre-monsoon 2007		Post-monsoon 2007		Pre-monsoon 2008		Post-monsoon 2008	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Herb cover	-0.813	0.094	-0.666	0.201	-0.850	0.068	-0.930	**0.022**
Richness	-0.889	**0.043**	-0.930	**0.022**	-0.925	**0.024**	-0.960	**0.009**
Plant height	-0.943	**0.016**	-0.881	**0.048**	-0.905	**0.035**	-0.967	**0.007**
Canopy cover	-0.835	0.078	-0.837	0.077	-0.801	0.103	-0.792	0.111
WIS	0.956	**0.011**	0.973	**0.005**	0.966	**0.007**	0.960	**0.009**
N score	-0.979	**0.004**	-0.982	**0.003**	-0.988	**0.002**	-0.917	**0.028**

	Lower Santa Cruz River							
	Pre-monsoon 2007		Post-monsoon 2007		Pre-monsoon 2008		Post-monsoon 2008	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Herb cover	-0.956	**0.011**	-0.746	0.148	-0.897	**0.039**	-0.835	0.078
Richness	-0.645	0.240	-0.850	0.068	-0.938	**0.018**	-0.971	**0.006**
Plant height	-0.955	**0.011**	-0.902	**0.036**	-0.954	**0.012**	-0.923	**0.025**
Canopy cover	0.904	**0.035**	0.888	**0.044**	0.898	**0.038**	0.880	**0.049**
WIS	0.948	**0.014**	0.929	**0.023**	0.986	**0.002**	0.886	**0.046**
N score	-0.978	**0.004**	-0.941	**0.017**	-0.987	**0.002**	-0.979	**0.004**

Table XV. Standardized beta coefficients from multiple regression analyses predicting traits of streamside plant communities based on distance from outfall and canopy cover at 10 sites (5 in the upper reach, 5 in the lower reach) along the effluent-dominated Santa Cruz River. Only significant results are shown. ( ) = Standard error.

Lower Santa Cruz River

	Herb cover		**Richness**		**Plant height**		**Wetland Indicator Score**		**N score**	
	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
pre-monsoon 2007:										
distance	-0.386 (0.425)	0.014	-0.364 (0.008)	p<0.001	-0.737 (0.229)	p<0.001	0.506 (0.005)	p<0.001	-0.742 (0.004)	p<0.001
canopy cover	----	----	----	----	----	----	----	----	----	----
post-monsoon 2007:										
distance	----	----	----	----	-0.466 (0.262)	p<0.001	0.391 (0.008)	0.016	-0.450 (0.009)	0.001
canopy cover	----	----	----	----	----	----	----	----	-0.275 (0.005)	0.043
pre-monsoon 2008:										
distance	-0.532 (0.281)	0.001	----	----	-0.632 (0.740)	p<0.001	0.595 (0.009)	p<0.001	-0.592 (0.007)	p<0.001
canopy cover	----	----	----	----	----	----	----	----	-0.275 (0.003)	0.016
post-monsoon 2008:										
distance	0.597 (0.292)	0.001	----	----	-0.807 (0.507)	p<0.001	0.696 (0.009)	p<0.001	-0.615 (0.008)	p<0.001
canopy cover	-0.554 (0.144)	0.002	-0.429 (0.008)	0.020	----	----	----	----	-0.209 (0.004)	0.070

Upper Santa Cruz River

	Herb cover		**Richness**		**Plant height**		**Wetland Indicator Score**		**N score**	
	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
pre-monsoon 2007:										
distance	-1.205 (0.476)	p<0.001	-0.945 (0.016)	p<0.001	-0.842 (0.537)	p<0.001	1.113 (0.010)	p<0.001	-0.875 (0.004)	p<0.001
canopy cover	-0.885 (0.197)	p<0.001	-0.431 (0.007)	0.004	----	----	0.328 (0.004)	0.001	----	----
post-monsoon 2007:										
distance	----	----	----	----	-0.473 (0.518)	0.012	0.553 (0.009)	p<0.001	-0.416 (0.013)	0.010
canopy cover	-0.317 (0.108)	0.002	----	----	-0.403 (0.210)	0.032	----	----	----	----
pre-monsoon 2008:										
distance	-0.645 (0.401)	p<0.001	-0.569 (0.020)	p<0.001	-0.666 0.355	p<0.001	1.073 (0.008)	p<0.001	-0.999 (0.007)	p<0.001
canopy cover	----	----	----	----	----	----	0.220 (0.003)	p<0.001	----	----
post-monsoon 2008:										
distance	----	----	----	----	-0.607 (0.321)	p<0.001	0.425 (0.008)	0.004	-0.809 (0.008)	p<0.001
canopy cover	-0.319 (0.184)	0.050	----	----	----	----	----	----	----	----

Table XVI. Comparison of the effects of river setting and elevation on streamside herbaceous community variables at perennial sites across the upper and lower effluent-dominated Santa Cruz River and non-effluent San Pedro. Bold values denote significance, p < 0.05, n = 3, each river.

		Pre-monsoon		**Post-monsoon**	
	df	*F*	*P*	*F*	*P*
Herbaceous cover					
River Setting	2	18.01	**0.010**	5.883	0.064
Elevation	2	1.803	0.277	1.629	0.304
River x Elevation	4	7.55	**<.001**	9.362	**<.001**
Plant height					
River Setting	2	9.424	**0.031**	7.588	**0.044**
Elevation	2	1.954	0.256	0.795	0.512
River x Elevation	4	6.997	**<.001**	10.28	**<.001**
Richness					
River Setting	2	19.51	**0.009**	22.59	**0.007**
Elevation	2	0.705	0.547	2.109	0.237
River x Elevation	4	2.92	**0.023**	1.271	0.284
Canopy Cover					
River Setting	2	2.866	0.169	3.244	0.145
Elevation	2	0.572	0.605	0.572	0.605
River x Elevation	4	66.75	**<.001**	101	**<.001**
Wetland Indicator Score					
River Setting	2	2.96	0.163	3.381	0.138
Elevation	2	1.979	0.253	1.91	0.262
River x Elevation	4	4.615	**0.002**	4.077	**0.004**
N Score					
River Setting	2	7.606	**0.043**	52.44	**0.001**
Elevation	2	0.582	0.600	6.458	0.056
River x Elevation	4	13.75	**<.001**	2.649	**0.036**

Table XVII. Comparison of the effects of streamflow and river setting on streamside herbaceous community variables across the upper and lower effluent-dominated Santa Cruz River and non-effluent San Pedro. Bold values denote significance, p $\leq$ 0.05, n = 3, each river.

		Pre-monsoon		**Post-monsoon**	
	df	*F*	*P*	*F*	*P*
Herbaceous cover					
River Setting	2	0.080	0.923	2.160	0.152
Flow Permanence	2	4.180	**0.016**	2.530	0.081
River x Flow	2	2.180	0.115	1.690	0.186
Plant height					
River Setting	2	4.830	0.025	2.830	0.093
Flow Permanence	2	6.820	**0.001**	3.570	**0.029**
River x Flow	2	2.600	0.076	5.460	**0.005**
Richness					
River Setting	2	0.910	0.427	7.510	**0.006**
Flow Permanence	2	0.270	0.762	0.040	0.956
River x Flow	2	0.680	0.508	1.770	0.173
Canopy Cover					
River Setting	2	0.030	0.968	0.020	0.979
Flow Permanence	2	6.190	**0.002**	5.310	**0.005**
River x Flow	2	7.850	**<.001**	7.480	**<.001**
Wetland Indicator Score					
River Setting	2	2.730	0.100	2.720	0.100
Flow Permanence	2	59.670	**<.001**	16.440	**<.001**
River x Flow	2	0.430	0.652	2.290	0.103
N Score					
River Setting	2	5.580	**0.017**	5.310	**0.019**
Flow Permanence	2	24.130	**<.001**	14.990	**<.001**
River x Flow	2	11.480	**<.001**	13.270	**<.001**

Table XVIII.ANOVA output comparing plant community variables across streamside (0-2 m), near (2-10 m) and far (10+ m) floodplain zones in the upper and lower effluent-dominated Santa Cruz River. Values are shown for pre-monsoon 2008 data. Bold values denote significance, alpha = 0.05, n = 7 (Upper Santa Cruz) and n=5 (Lower Santa Cruz).

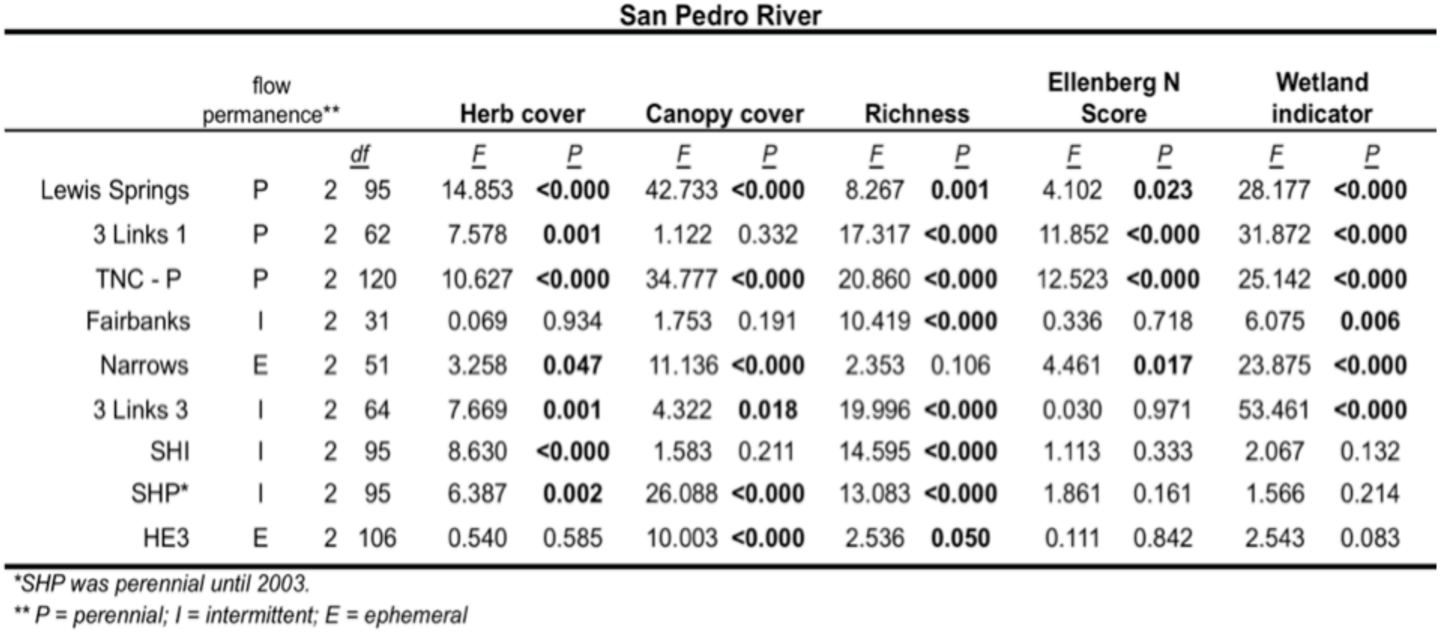
UPPER SANTA CRUZ RIVER

	downstream distance (km)			Herb cover		Canopy cover		Richness		Ellenberg N Score		Wetland indicator status	
		df		*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Santa Fe Ranch	-10	2	65	0.157	0.855	0.317	0.730	0.147	0.864	0.036	0.964	2.341	0.365
Calabasas	-5	2	68	3.321	**0.042**	1.249	0.635	0.935	0.398	0.396	0.675	1.023	0.365
Santa Gertudis	15	2	39	11.175	**<0.001**	3.335	**0.047**	18.160	**<0.001**	14.552	**<0.001**	17.104	**<0.001**
Chavez Siding	25	2	39	78.859	**<0.001**	8.824	**<0.001**	24.240	**<0.001**	12.498	**<0.001**	29.864	**<0.001**
Amado	35	2	63	109.070	**<0.001**	2.236	0.116	30.952	**<0.001**	16.495	**<0.001**	112.766	**<0.001**
Continental	45	2	37	4.380	**0.020**	2.436	0.102	8.156	**<0.001**	4.114	**0.025**	15.223	**<0.001**
Sahuarita	55	2	33	2.931	**0.080**	0.579	0.565	1.589	0.220	3.101	0.066	0.912	0.412

LOWER SANTA CRUZ RIVER

		df		*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Ina	8	2	48	19.415	**<0.001**	2.300	0.112	3.464	**0.040**	20.808	**<0.001**	23.278	**<0.001**
Avra Valley	15	2	45	85.408	**<0.001**	1.935	0.157	13.631	**<0.001**	15.409	**<0.001**	23.714	**<0.001**
Hardin	30	2	43	8.750	**0.001**	1.406	0.257	9.258	**<0.001**	16.145	**<0.001**	33.511	**<0.001**
Sasco	45	2	34	6.251	**0.005**	57.789	**<0.001**	0.200	0.820	17.868	**<0.001**	7.691	**<0.001**
Wheeler	60	2	38	12.474	**<0.001**	51.059	**<0.001**	5.140	0.011	28.64	**<0.001**	23.671	**<0.001**

Table XIX. ANOVA output comparing plant community variables across streamside (0-2 m), near (2-10 m) and far (10+ m) floodplain zones for intermittent and perennial sites in the upper and lower basins of the San Pedro River. Values are shown for pre-monsoon 2008 data. Bold values denote significance, alpha = 0.05, n = 9.



San Pedro River														
	flow permanence**			Herb cover		Canopy cover		Richness		Ellenberg N Score		Wetland indicator	
		df		*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Lewis Springs	P	2	95	14.853	**<0.000**	42.733	**<0.000**	8.267	**0.001**	4.102	**0.023**	28.177	**<0.000**
3 Links 1	P	2	62	7.578	**0.001**	1.122	0.332	17.317	**<0.000**	11.852	**<0.000**	31.872	**<0.000**
TNC - P	P	2	120	10.627	**<0.000**	34.777	**<0.000**	20.860	**<0.000**	12.523	**<0.000**	25.142	**<0.000**
Fairbanks	I	2	31	0.069	0.934	1.753	0.191	10.419	**<0.000**	0.336	0.718	6.075	**0.006**
Narrows	E	2	51	3.258	**0.047**	11.136	**<0.000**	2.353	0.106	4.461	**0.017**	23.875	**<0.000**
3 Links 3	I	2	64	7.669	**0.001**	4.322	**0.018**	19.996	**<0.000**	0.030	0.971	53.461	**<0.000**
SHI	I	2	95	8.630	**<0.000**	1.583	0.211	14.595	**<0.000**	1.113	0.333	2.067	0.132
SHP*	I	2	95	6.387	**0.002**	26.088	**<0.000**	13.083	**<0.000**	1.861	0.161	1.566	0.214
HE3	E	2	106	0.540	0.585	10.003	**<0.000**	2.536	**0.050**	0.111	0.842	2.543	0.083

**SHP was perennial until 2003.*

*** P = perennial; I = intermittent; E = ephemeral*

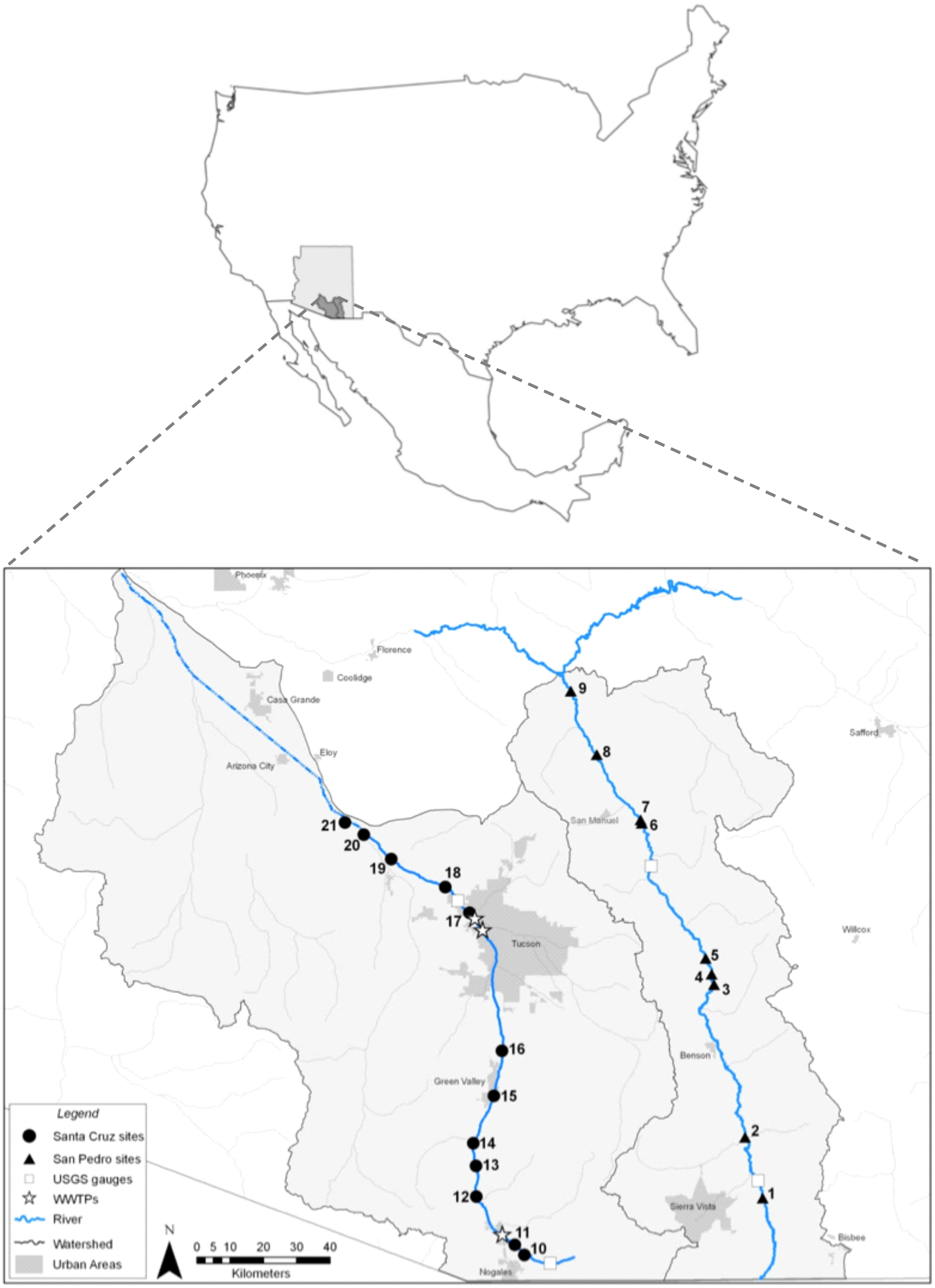


Figure 22. Map of effluent-dominated study river (Santa Cruz) and control river (San Pedro) showing locations of study sites, wastewater treatment facilities (WWTPs) and USGS stream gages. Site information is listed in Table 1. Climate and hydrologic information can be found in Table 2.

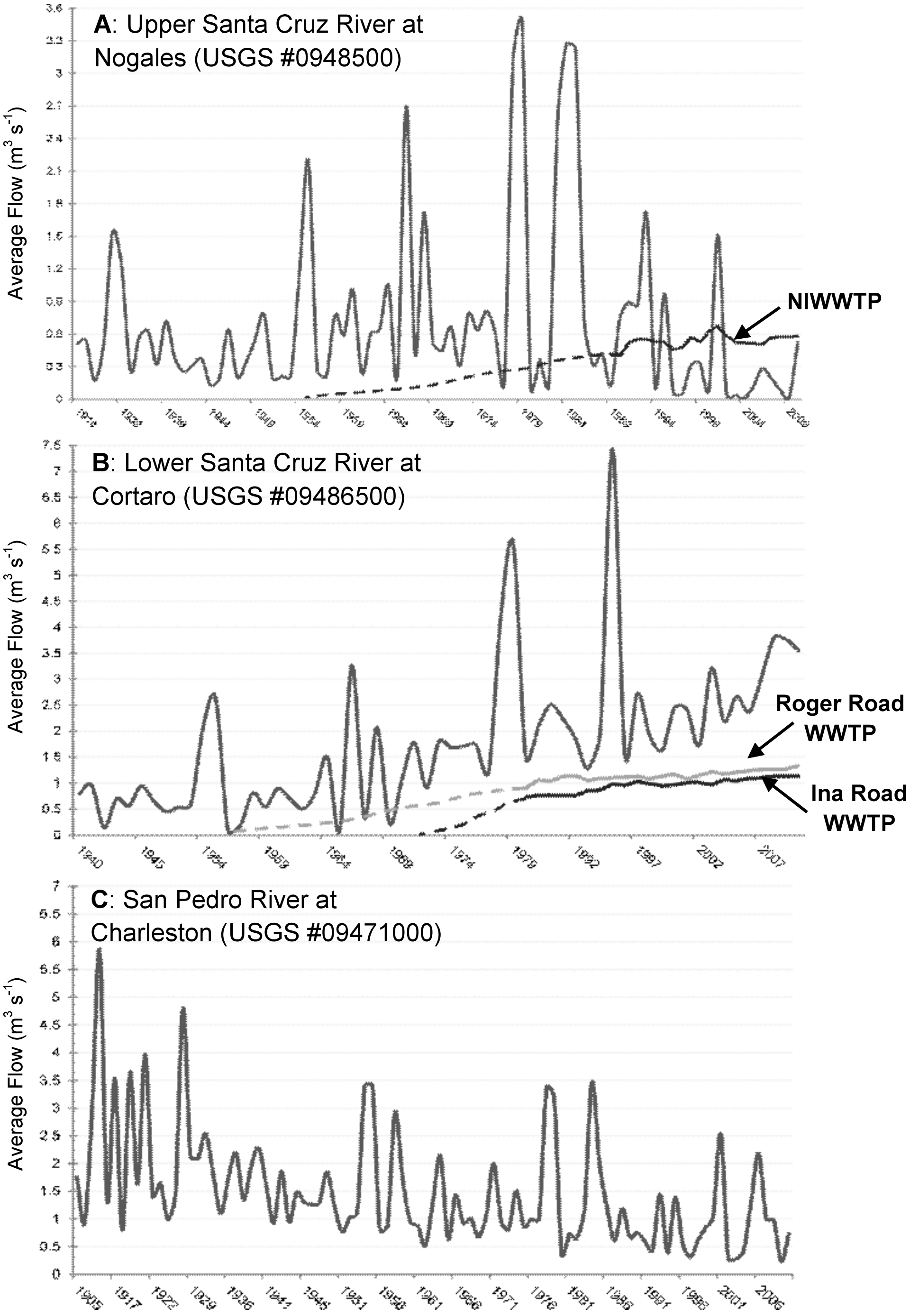


Figure 23. Average annual streamflow for the Santa Cruz and San Pedro Rivers. Effluent contributes a steady and increasing supplement to the surface flow of the Santa Cruz River in both its upper (A) and lower (B) reaches. For the upper reach, the stream gage is located upstream of the point of effluent release. In the lower reach, the gage measurements reflect the addition of effluent.

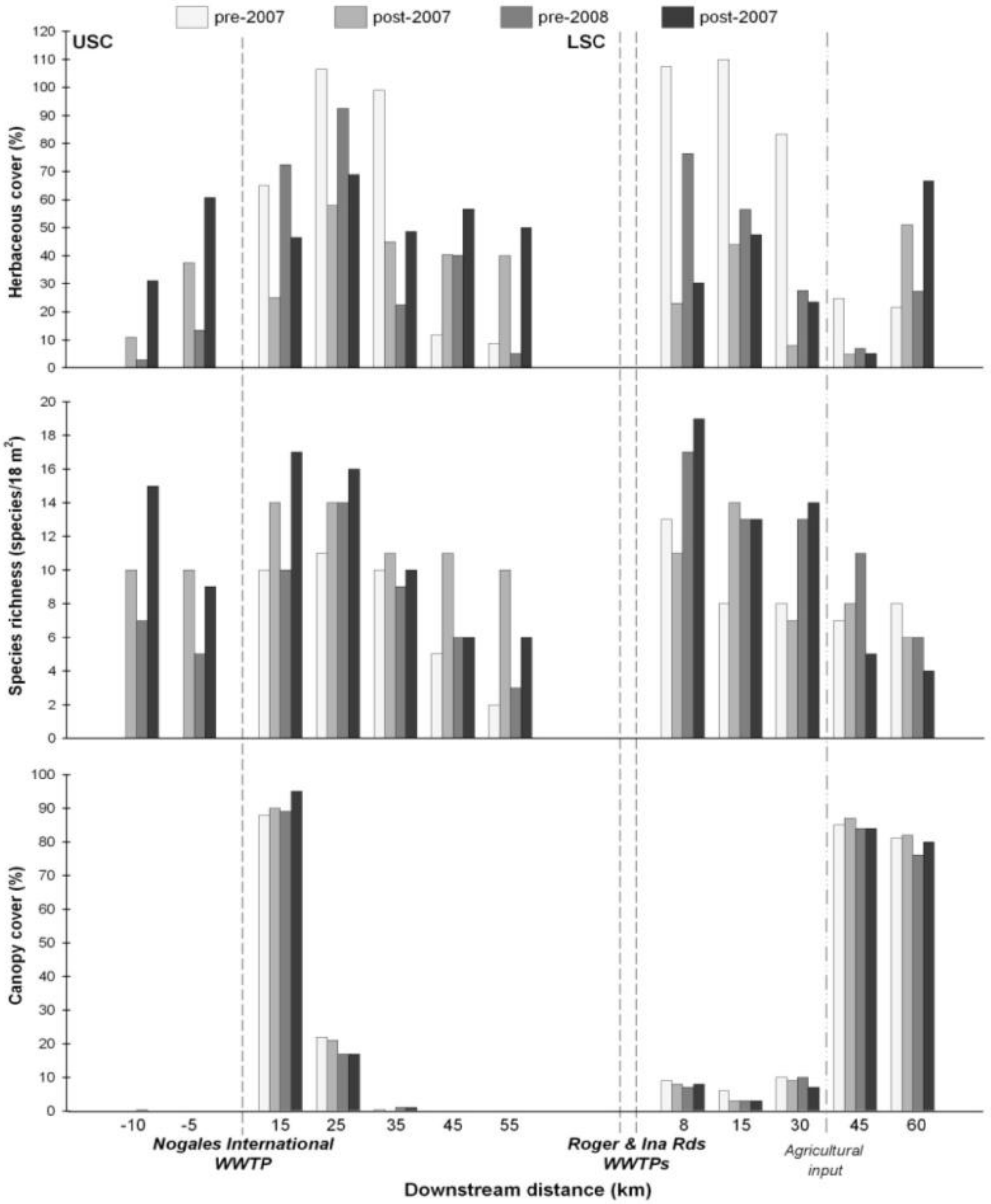


Figure 24. Relationship of streamside herbaceous cover, species richness, and canopy cover with increasing distance from point of effluent discharge for the upper and lower Santa Cruz River. Results are from pre- and post-monsoon seasons in 2007 & 2008. Table 3 shows corresponding correlation data.

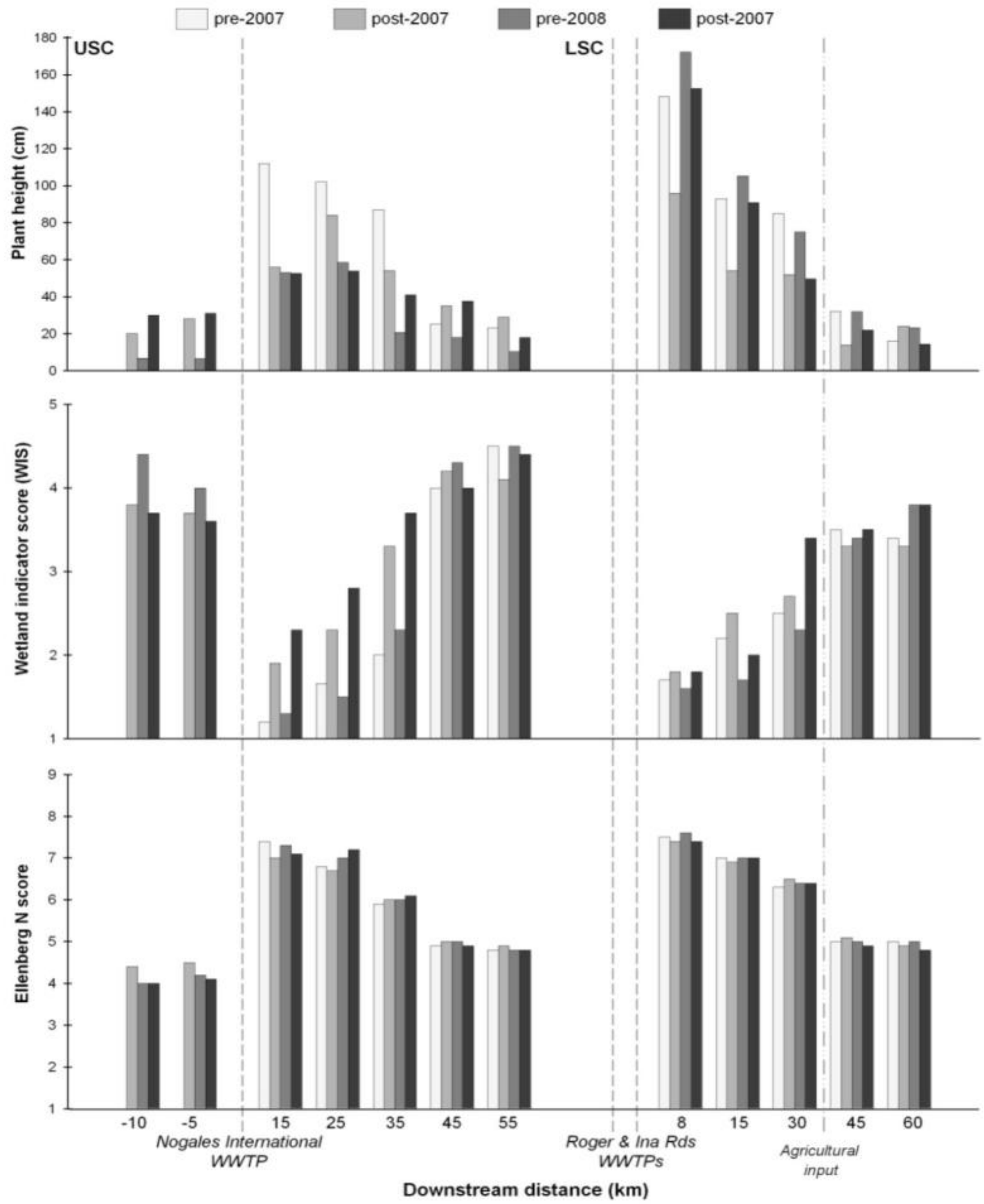


Figure 25. Relationship of plant height, WIS, and Ellenberg N score with increasing distance from point of effluent discharge for the upper and lower Santa Cruz River. Results are from pre- and post-monsoon seasons in 2007 & 2008. Table 3 shows corresponding correlation data.

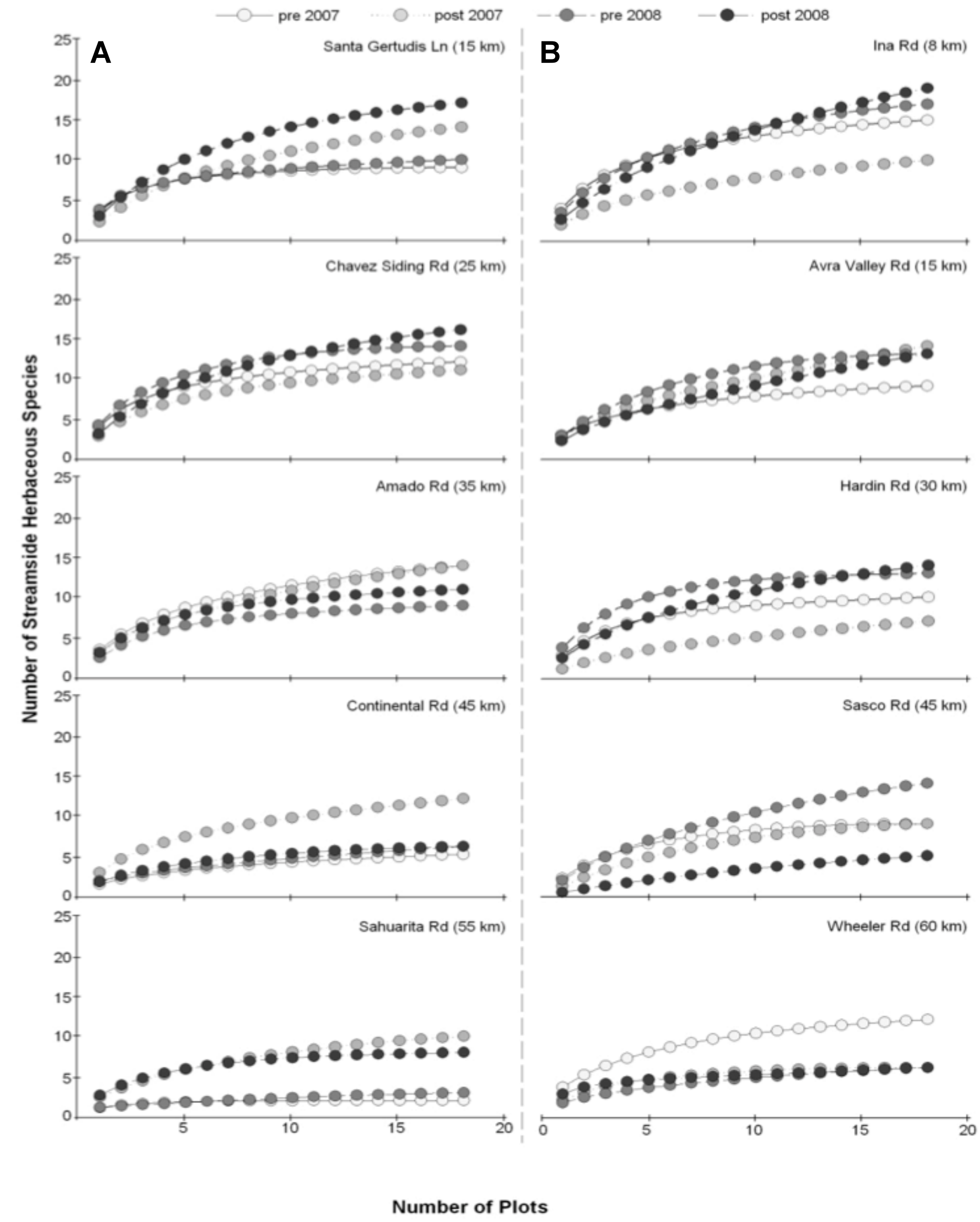


Figure 26. Species accumulation curves for streamside herbaceous plots (n=18, 10 effluent-dominated sites) in the (A) upper and (B) lower Santa Cruz River. Results are from pre- and post-monsoon sampling in 2007 & 2008.

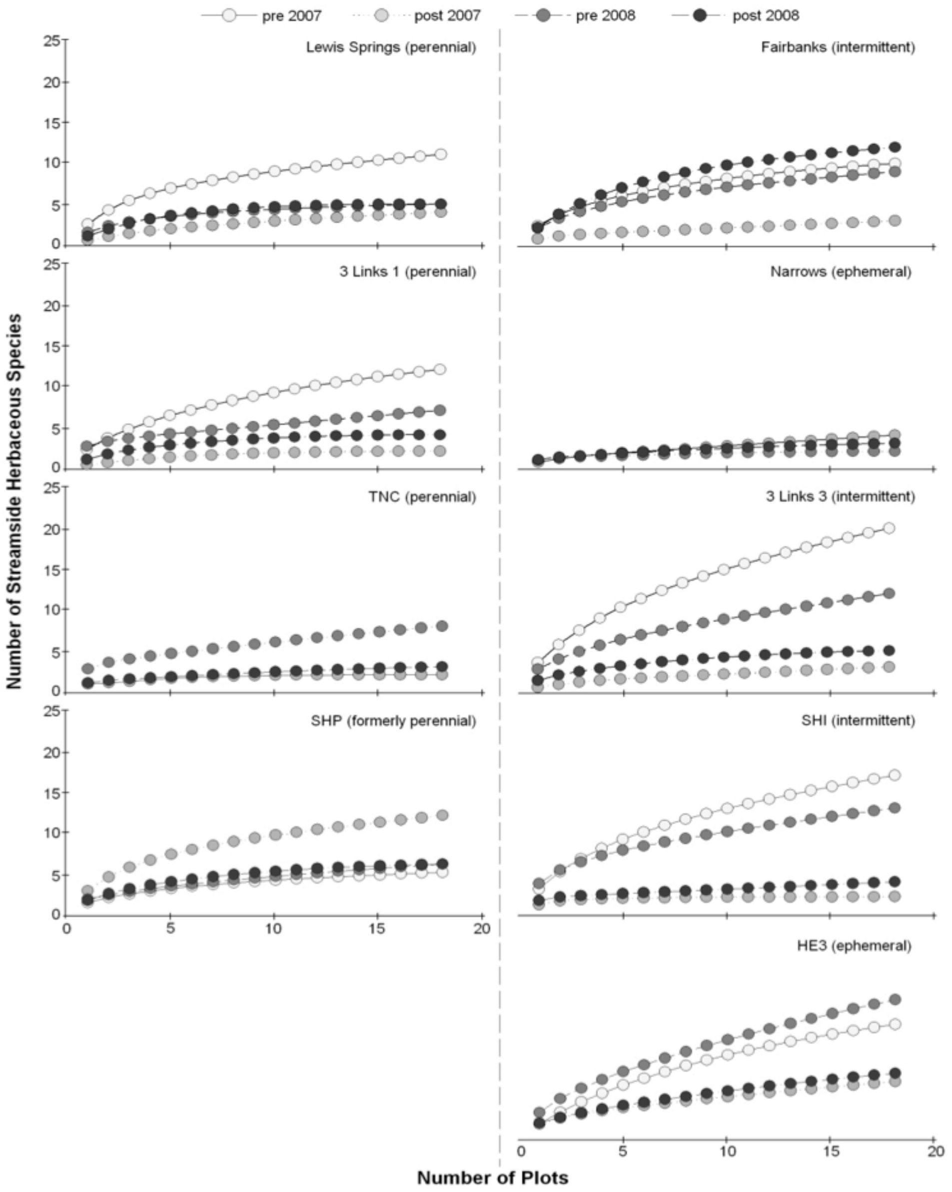


Figure 27. Species accumulation curves for streamside herbaceous plots (9 sites, n=18) on the San Pedro River. Results are from pre- and post-monsoon sampling in 2007 & 2008.

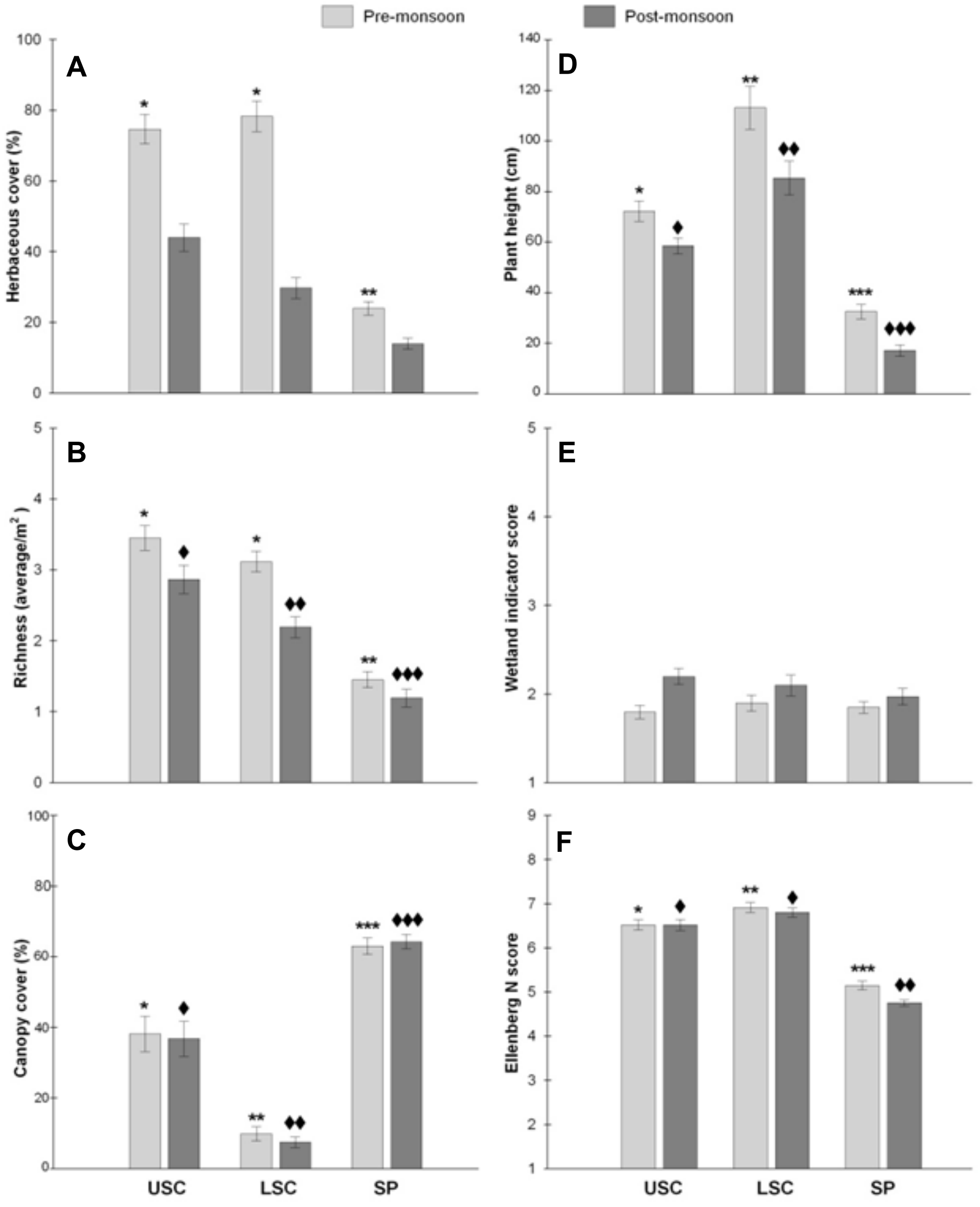


Figure 28. Pre- and post-monsoon comparisons of streamside plant community metrics at perennial sites in the upper Santa Cruz (USC), lower Santa Cruz (LSC), and San Pedro (SP) Rivers. Significant differences are highlighted with * for pre monsoon and ♦ for post monsoon data. Error bars = +/- 1 SE

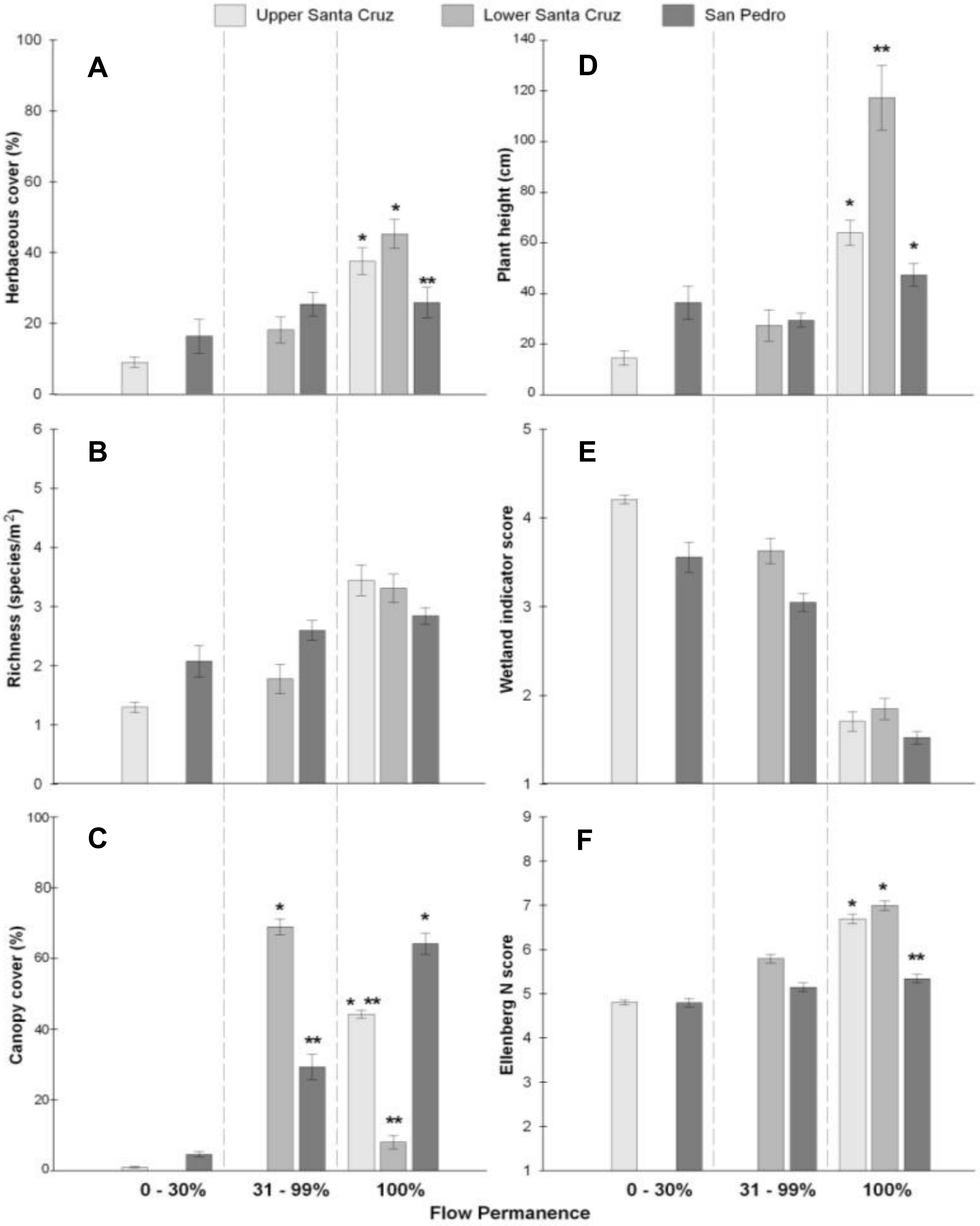


Figure 29. Pre-monsoon comparisons of plant community metrics at sites with varying flow conditions in the upper Santa Cruz (USC), lower Santa Cruz (LSC), and San Pedro (SP) Rivers. Significant differences are highlighted with * for pre monsoon data. Error bars = +/- 1 SE

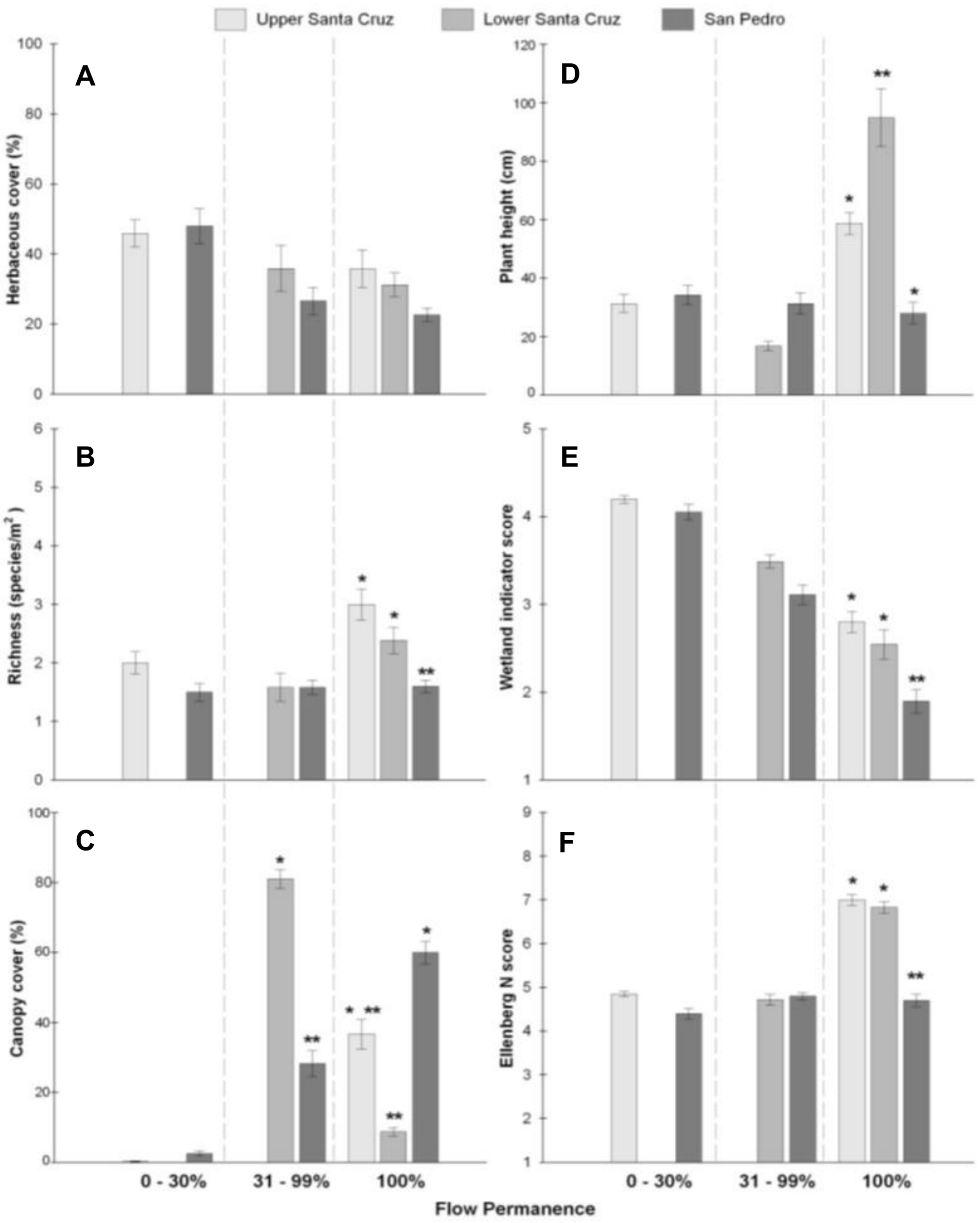


Figure 30. Post-monsoon comparisons of plant community metrics at sites with varying flow conditions in the upper Santa Cruz (USC), lower Santa Cruz (LSC), and San Pedro (SP) Rivers. Significant differences are highlighted with * for post monsoon data. Error bars = +/- 1 SE

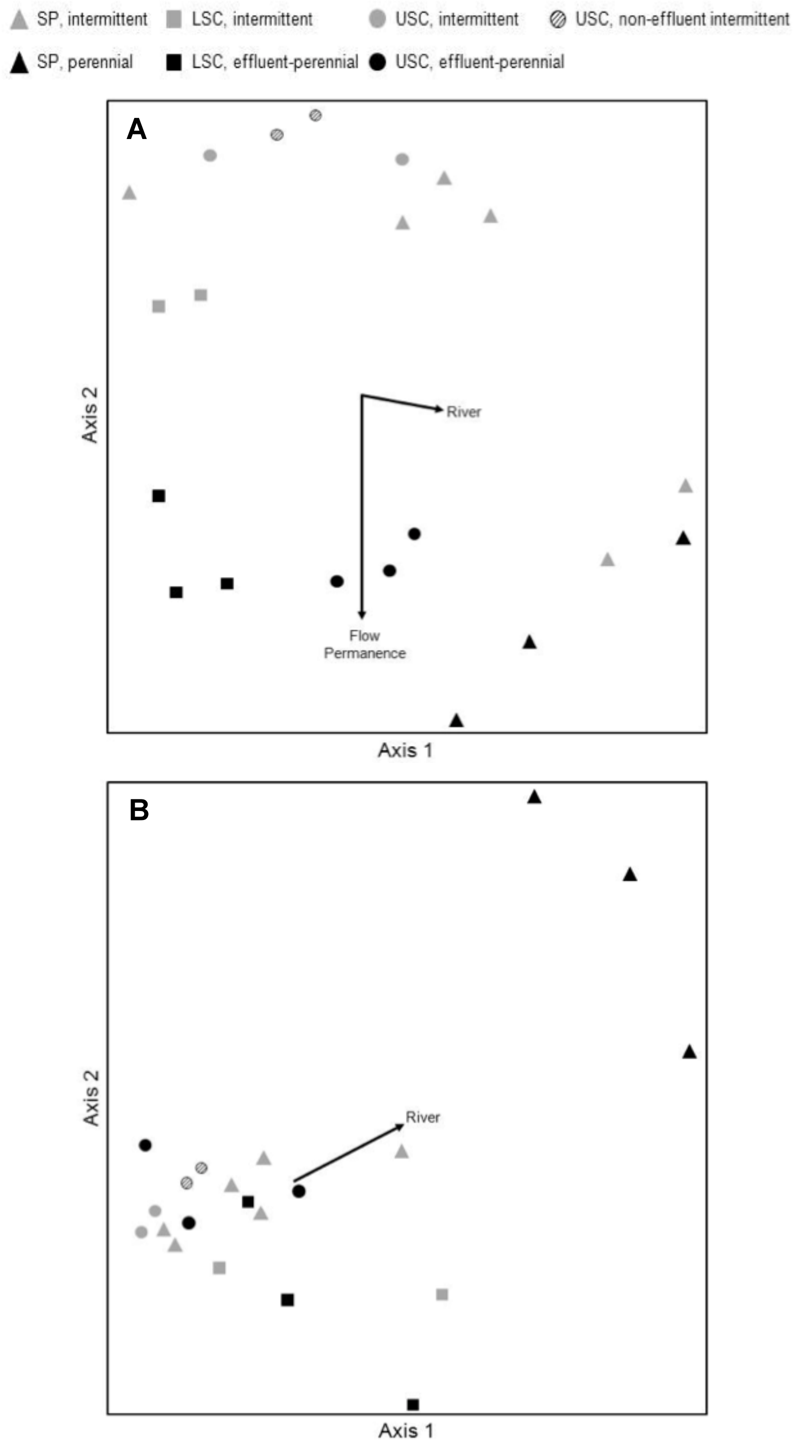


Figure 31. NMS ordination for Axis 1 and 2 of (A) pre- and (B) post-monsoon streamside herbaceous data sampled in 2008 along the upper Santa Cruz (n = 7), lower Santa Cruz (n = 5) and San Pedro Rivers (n = 9; 21 total sites). Correlation vectors are plotted if $r^2 > 0.10$.

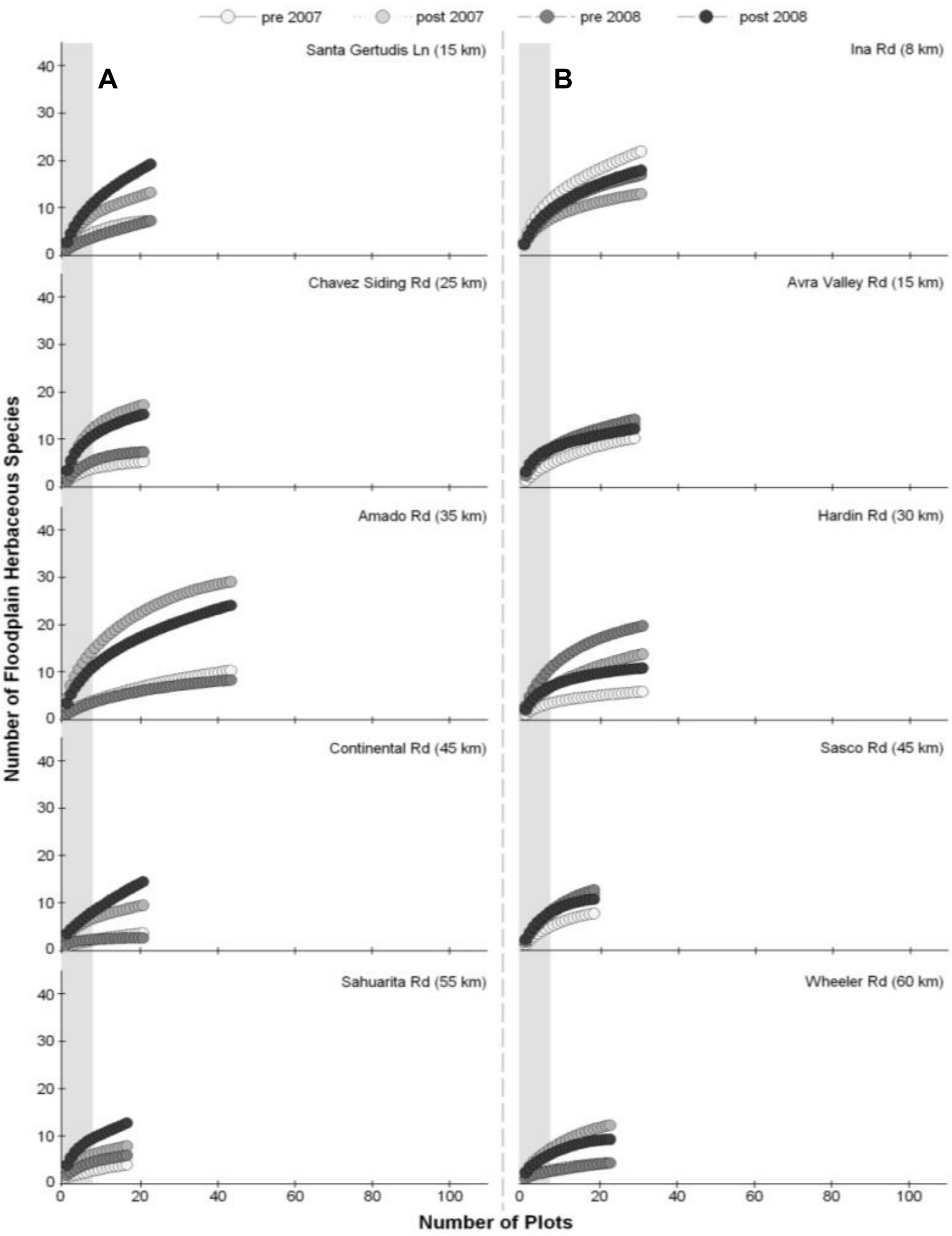


Figure 32. Species accumulation curves for floodplain herbaceous plots in the (A) upper and (B) lower Santa Cruz River. Results are from pre- and post-monsoon sampling in 2007 & 2008. The gray bar indicates the “near” floodplain zone (2-10 meters).

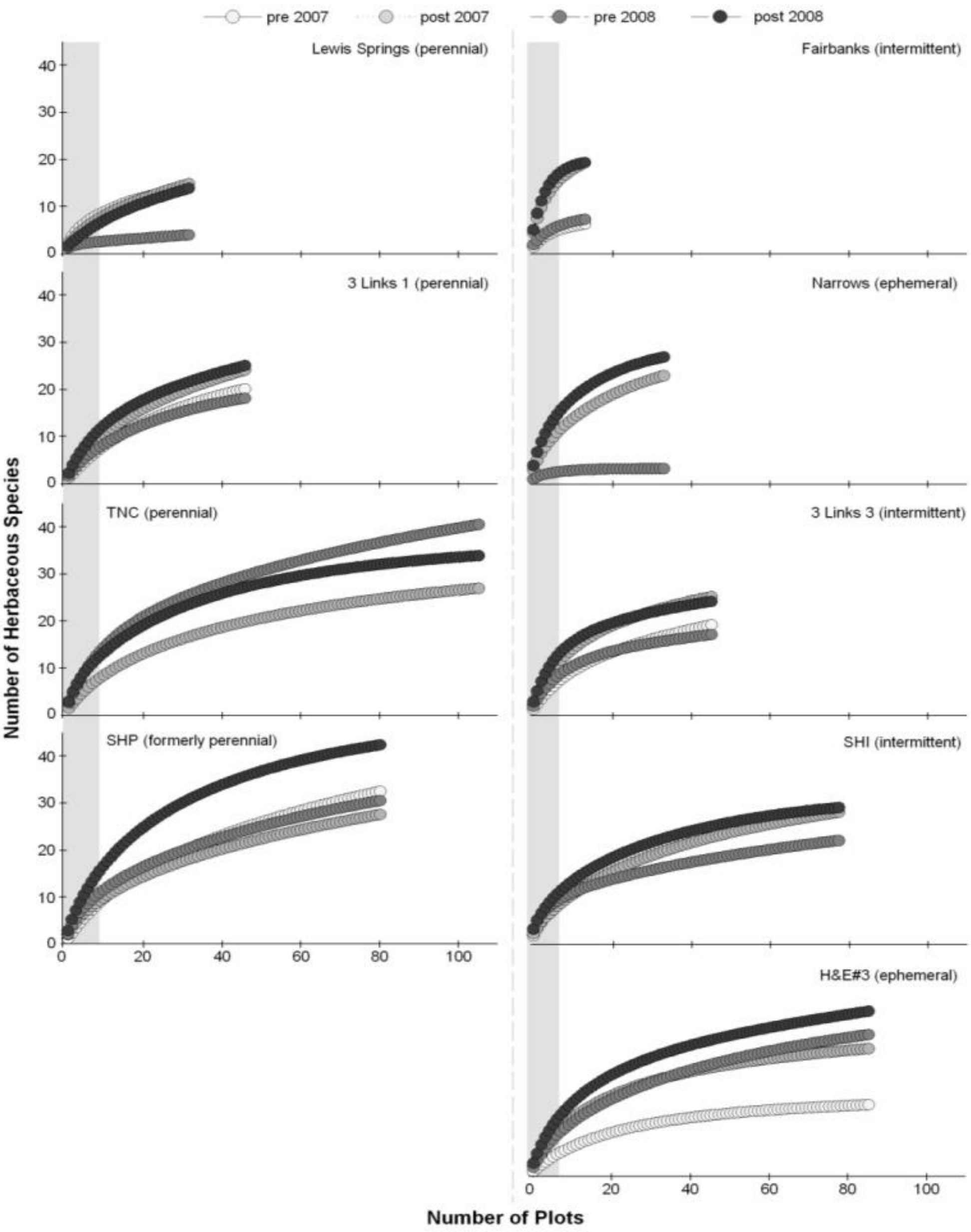


Figure 33. Species accumulation curves for floodplain herbaceous plots on the non-effluent San Pedro River. Results are from pre- and post-monsoon sampling in 2007 & 2008. The gray bar indicates the “near” floodplain zone (2-10 meters).

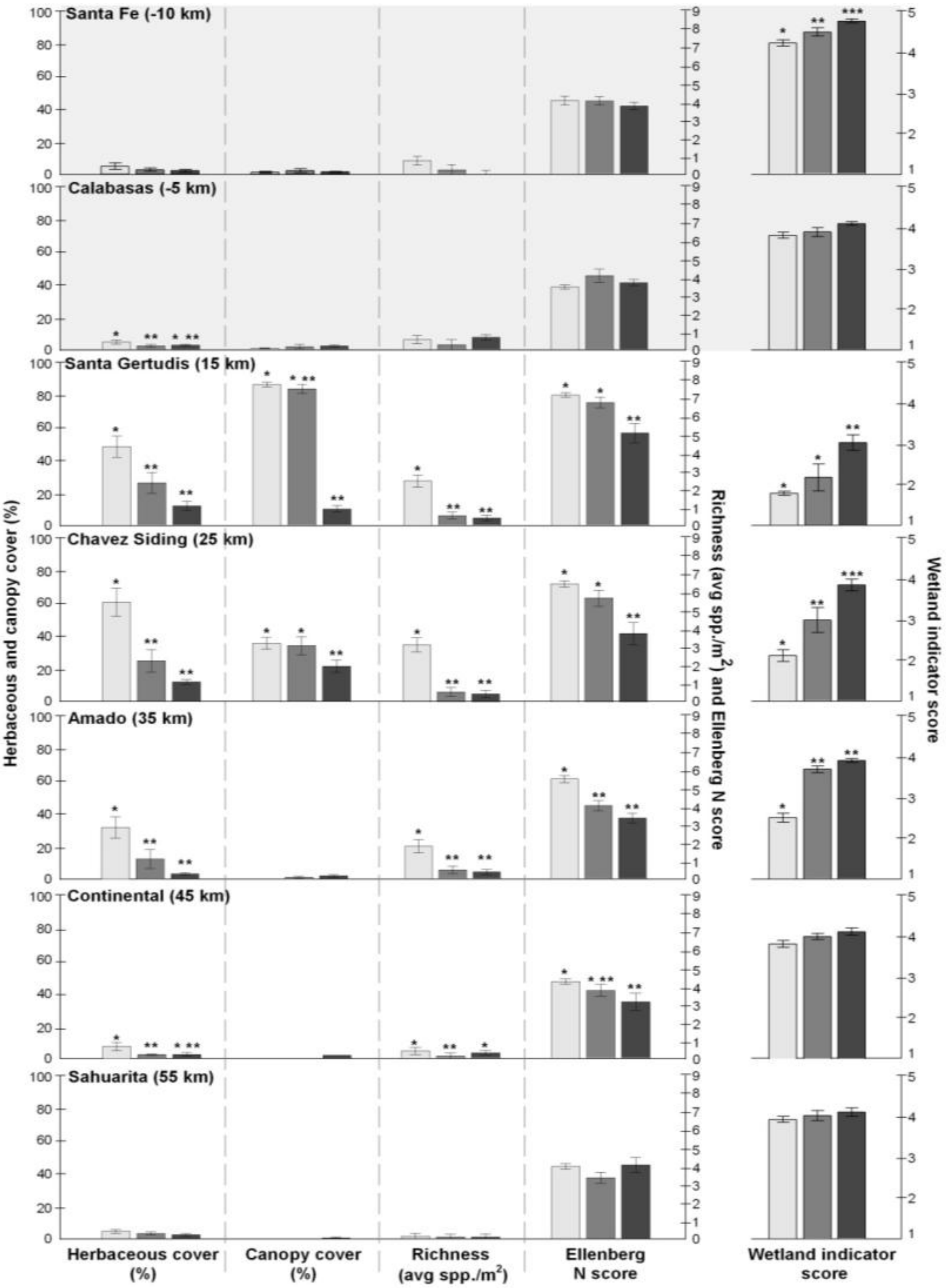


Figure 34. Patterns of plant community variables across floodplains for pre-monsoon 2008 data in the upper Santa Cruz River. Significant differences ($p<0.05$) from Tukey pairwise comparison are indicated by different numbers of asterisks (*). Sites with a gray background are within-river non-effluent controls located upstream of NIWWTP.

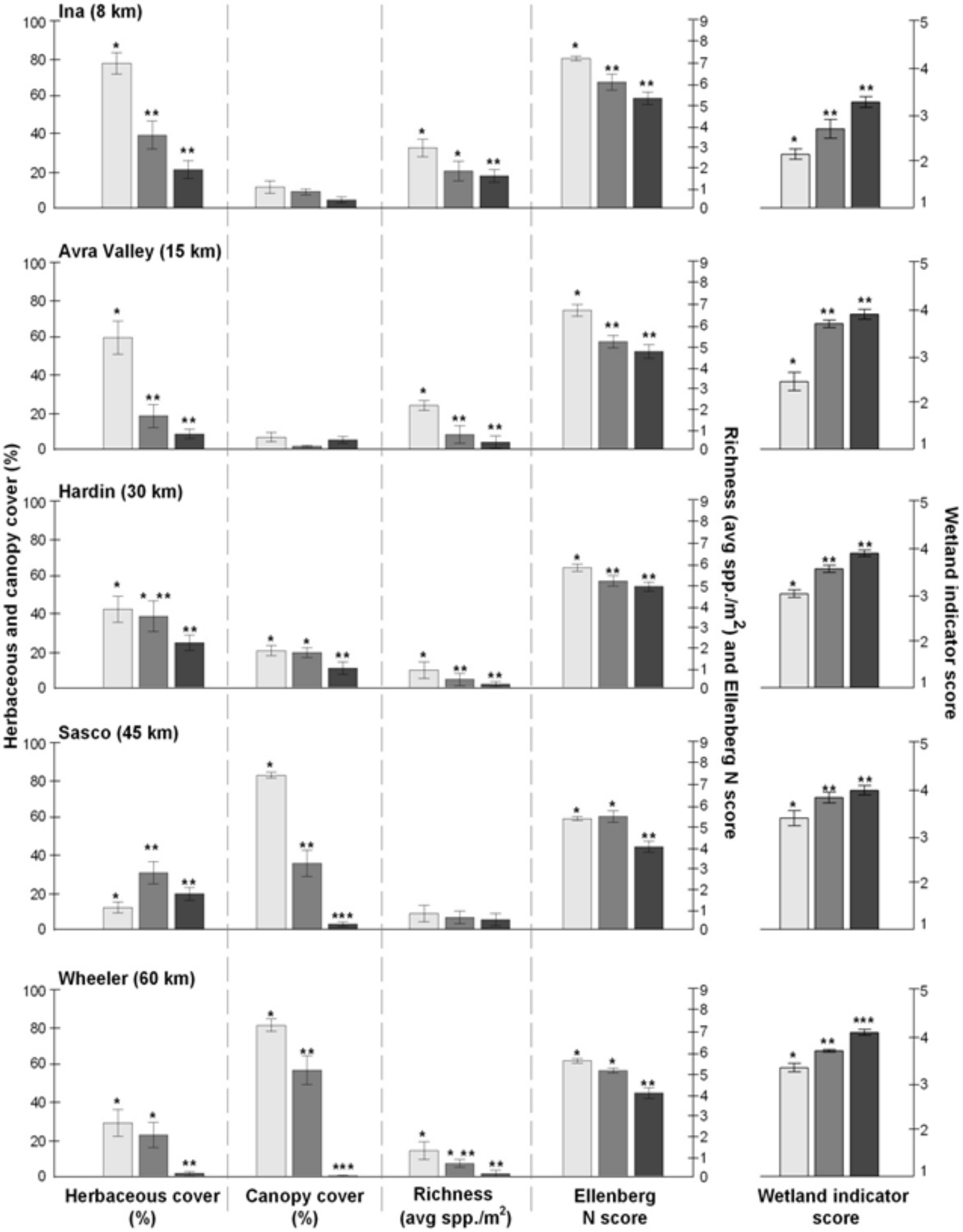


Figure 35. Patterns of plant community variables across floodplains for pre-monsoon 2008 data in the lower Santa Cruz River. Significant differences (p<0.05) from Tukey pairwise comparison are indicated by different numbers of asterisks (*).

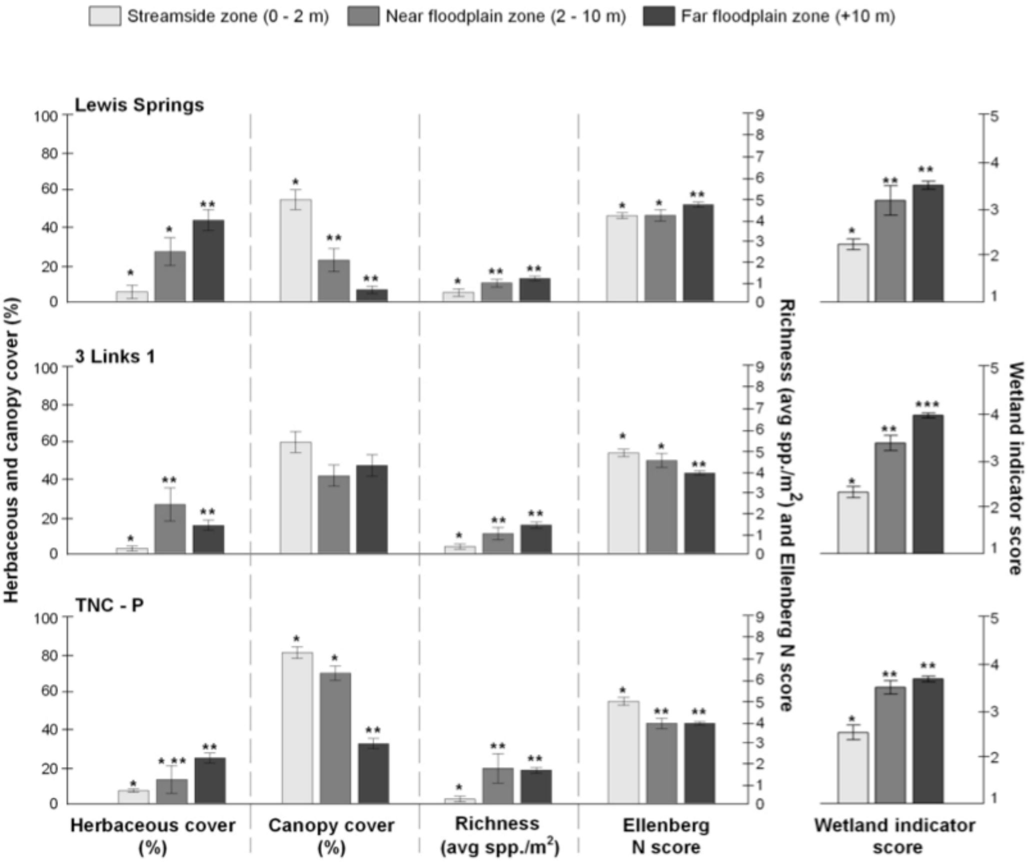


Figure 36. Patterns of plant community variables across floodplains for pre-monsoon 2008 data for perennial sites on the San Pedro River. Significant differences ($p<0.05$) from Tukey pairwise comparisons are indicated by different numbers of asterisks (*).

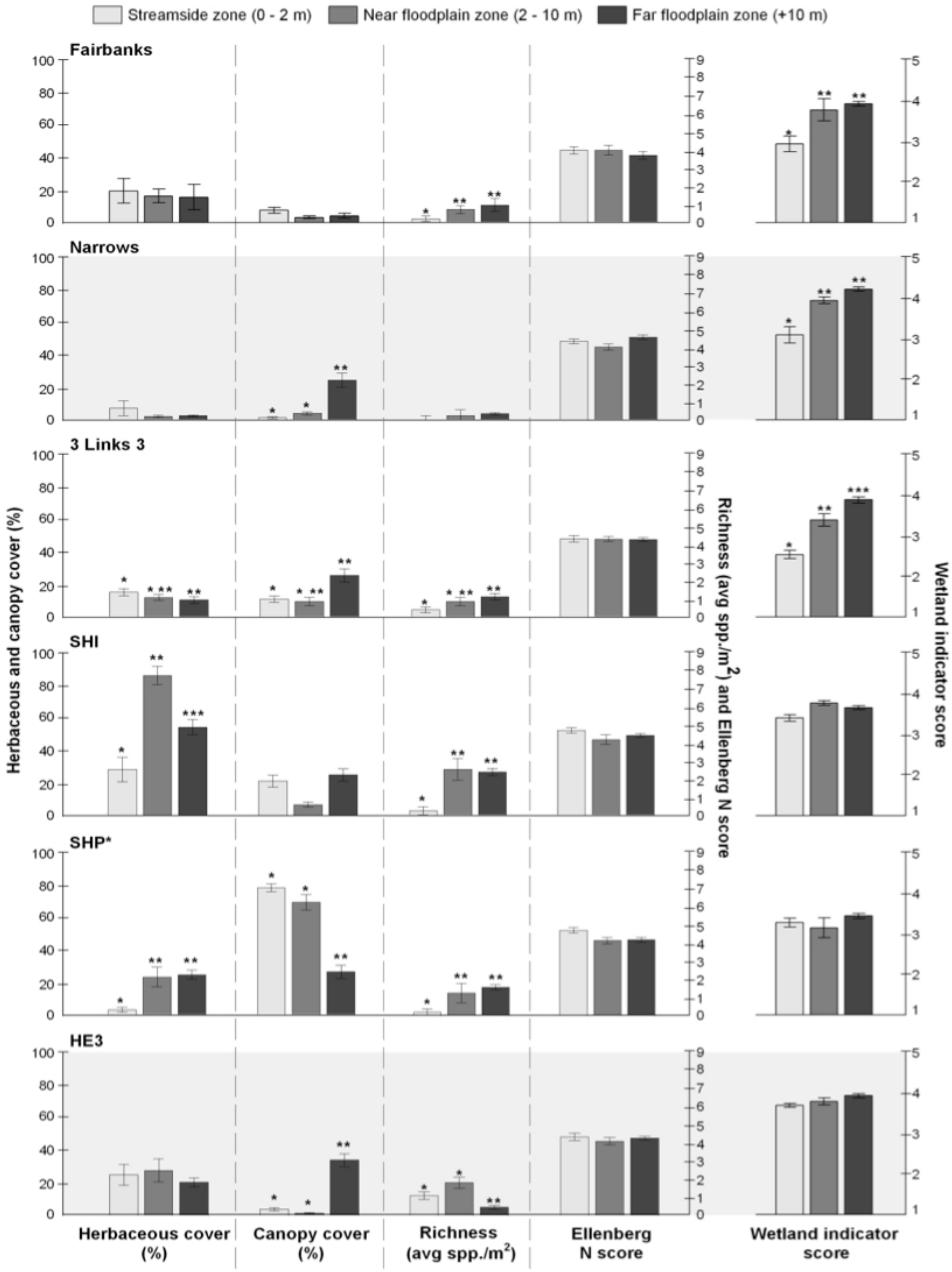


Figure 37. Patterns of plant community variables across floodplains for pre-monsoon 2008 data for intermittent sites on the San Pedro River. Significant differences ($p<0.05$) from Tukey pairwise comparisons are indicated by different numbers of asterisks (*). Sites with a gray background are ephemeral. **SHP has been intermittent since 2003.*

5. SPATIAL AND TEMPORAL VEGETATION PATTERNS OF RIPARIAN VEGETATION IN EFFLUENT-DOMINATED WATERWAYS

ABSTRACT

Riparian ecosystems are among the most diverse and threatened ecosystems in the southwestern United States and consequently the focus of much conservation and restoration efforts. During the twentieth century stream diversion and groundwater withdrawals have lowered water tables in stream aquifers and negatively impacted the abundance and distribution of the many riparian tree species on dryland rivers. Other alterations, such as the release of effluent from municipal wastewater treatment facilities, have provided stable, perennial base flows supporting the development of riparian habitat downstream of the treatment plant. Little is known about the ecological dynamics of these effluent-dominated riparian ecosystems and our goal was to assess how increased water availability from effluent released into the Santa Cruz River has influenced spatial and temporal patterns of vegetation change. Using a time-series of aerial photographs (1955–2010) combined with collected field data we quantified changes in extent, abundance, and composition of riparian woody vegetation in the riparian zone of an effluent-dominated waterway that spans two hydrological settings (deep groundwater disconnected to the stream flow, and shallow groundwater hydraulically connected to the stream flow). We used the San Pedro River, with its similar hydrologic regime and geographic setting, as our non-effluent reference system.

Analysis indicated that species richness was similar between the systems. Hydric pioneers, including *Populus fremontii* and *Salix gooddingii*, were dominant at perennial sites on both rivers, particularly those with shallow groundwater. Riparian vegetation in the shallow-groundwater upper Santa Cruz clearly declined with increasing distance from effluent release while patterns in the deep-groundwater lower Santa Cruz were confounded by the additional agricultural input and an extremely channelized floodplain closest to the treatment facility. In floodplains of the effluent-dominated system, there was a distinct shift toward more xeric species with increasing stream flow intermittency and distance from the low-flow channel. Differential response between the upper and lower reaches of the effluent dominated Santa Cruz indicates that water availability is the driving variable of downstream riparian plant community structural development. This study revealed that effluent has contributed to the restoration and maintenance of woody vegetation on the Santa Cruz, with cottonwood-willow gallery forest more successfully maintained in shallow groundwater settings. Analysis of spatial and temporal interactions of geomorphic, hydrological and terrestrial processes provides the long-term perspective needed to inform conservation and management of rivers subsidized by effluent.

INTRODUCTION

Riparian ecosystems are recognized as biologically important components of landscapes worldwide that link aquatic and terrestrial habitats and serve as interfaces that influence, and are influenced by, these systems (Bendix and Hupp, 2000). As a result, riverine ecosystems are dynamic; fluvial processes including, flooding impact the spatial and structural heterogeneity of riparian plant communities by shaping geomorphic, topographic and biological features within the floodplain (Bendix and Hupp, 2000; Latterell *et al.*, 2006; Charron *et al.*, 2008; Stromberg *et al.*, 2008). In addition to fluvial dynamics, water availability is an important driver that impacts the area, composition, and age structure of riparian plant communities, particularly in arid and semi-arid regions (Sala *et al.*, 2000; Webb *et al.*, 2007).

In the semi-arid southwestern United States, stream diversion and groundwater withdrawals for urban, agricultural, and industrial uses have converted many perennial rivers to intermittent or ephemeral systems and lowered water tables in stream aquifers. These changes have affected abundance and distribution of the many riparian tree species that are phreatophytes, meaning they extract water from aquifers or the capillary fringe above the water table and are particularly sensitive to subsurface water availability (Meyer *et al.*, 1999). The phreatophytes that grow along rivers of the southwestern United States, which include *Salix gooddingii* (Goodding willow), *Populus fremontii* (Fremont cottonwood), *Tamarix ramosissima* (tamarisk), and *Prosopis velutina* (velvet mesquite), differ in root depth and architecture, water use rate, tolerance to drought and fluctuating water tables, and in their capacity to shift between seasonally varying water sources (Lite and Stromberg, 2005). *Salix* and *Populus* are considered to be obligate phreatophytes, requiring permanently available shallow ground water, while *Tamarix* and *Prosopis,* deep-rooted, facultative phreatophytes that obtain water from saturated and unsaturated soil, are physiologically adapted to a higher degree of water stress (Busch *et al.*, 1992; 2001a; Snyder and Williams, 2000; Stromberg *et al.*, 2008). Extraction of freshwater, combined with episodic drought, have shifted conditions suitable for maintaining forests of the pioneer trees, *Populus* and *Salix*, and in some settings, these forests have been replaced by shrublands or woodlands of more drought-tolerant taxa.

Paradoxically, while societal water demands have led to the contraction and, in some cases, complete disappearance of areas supporting riparian forests (Busch and Smith, 1995; Logan, 2002; Webb and Leake, 2006; Webb *et al.*, 2007), urban centers are producing large volumes of treated wastewater, which is often released into nearby stream channels. This dynamic has led to the emergence of effluent-dominated waterways, or rivers that derive a large percentage of their surface flows from the daily production and release of effluent into a stream channel. Effluent-dominated systems are fundamentally different from the intermittent or ephemeral streams they displace. Effluent is both nutrient rich and continuously released, fluxing diurnally with urban consumption patterns. High nitrogen levels can benefit riparian vegetation by stimulating growth (Patten *et al.*, 1998; Marler *et al.*, 2001) and can also foster biological activity within the channel that can lead to the formation of clogging layers in surface sediments (Boulton *et al.*, 1998; Hancock, 2002). These clogging layers can act as a seal the bottom of the stream channel, decreasing infiltration and recharge and hindering the connection between surface water, subflow, and groundwater, changing conditions for phreatophytic plants (Lacher, 1996; Brunke and Gonser 1997; Boulton *et al.*, 1998). Although *Populus*, *Salix* and other riparian trees are primarily phreatophytic in natural river settings, stream base flows and perched aquifers can be a water source for their growth at the stream edge (Smith *et al.*, 1991). Physiological responses of phreatophytes and shifts in riparian plant community structure to declines in surface flow and groundwater levels have been well studied, but there is little knowledge about how riparian vegetation in different hydrologic settings responds to long-term, continuous inflows of effluent. A lack of understanding about the dynamics of effluent-dominated streams underscores the growing need for suitable methods to evaluate the ecological integrity of these systems (Brooks *et al.*, 2006). This knowledge gap is particularly compelling within the context of prolonged drought and increasing freshwater demands, which may remove the effluent currently being discharged into river channels.

Riparian systems can be understood through spatial and temporal interactions of geomorphic, hydrological and terrestrial processes (Gregory *et al.*, 1991; Ward *et al.*, 2002). Using the effluent-dominated Santa Cruz River in the semi-arid southwestern United States as our study river, our research investigated spatial and temporal patterns of woody vegetation in the riparian zone of an effluent-dominated waterway that spans two hydrological settings (deep groundwater disconnected to the stream flow, and shallow groundwater hydraulically connected to the stream flow). We used the San Pedro River, with its similar hydrologic regime and geographic setting, as our non-effluent control. Grounding our work in both community and landscape ecology, we investigated how long-term effluent subsidy, land use, and management practices are interacting to structure riparian forest patterns on an effluent-dominated, dryland river. Our objectives were to increase understanding of the ecological effects of the continuous release of treated wastewater in these two settings by answering the following questions:

1. How do spatial and temporal patterns of woody riparian vegetation of effluent-dominated waterways differ from non-effluent rivers in the southwestern United States?
2. Are riparian forests and woody plant abundance and composition different in effluent-dominated systems compared to non-effluent systems?

3. Within the effluent-dominated system, how do woody vegetation patterns vary longitudinally from the point of discharge in different hydrologic settings?
4. How does woody vegetation in an effluent-dominated waterway vary laterally across the floodplain, and do these zonal patterns differ from that in control streams?

We expected the following: (1) shifts in vegetation from phreatophytic species to other woody vegetation would be highest in floodplains of deep-groundwater effluent-dominated systems. (2) Woody vegetation abundance (basal area, stem density, canopy cover) would decline within the effluent dominated river reaches with increasing distance from the point of discharge, and composition would shift away from hydric pioneers with increasing distance and flow intermittency. (3) Across the riparian corridor, near channel zones would support the highest woody vegetation and would decline most sharply with distance from the channel for the effluent-dominated reach in the deep-groundwater basin. The central aim of this research is to inform natural resource management and contribute to ecological understanding of effluent-dominated riparian systems through analysis of vegetation change at multiple temporal and spatial scales.

METHODS

Study Design

We used two methods for contrasting structure and dynamics of woody riparian plant communities between the floodplains of an effluent-dominated riparian ecosystem with a shallow water table (Upper Santa Cruz reach), an effluent-dominated riparian ecosystem with a deep water table (Lower Santa

Cruz reach), and a non-effluent control. First, we analyzed temporal and spatial changes in patch types over a 50-year period using Geographic Information Systems (GIS). Secondly, we sampled woody vegetation traits in the field to explore longitudinal community patterns in the effluent-dominated systems and to contrast lateral floodplain patterns across the three river settings.

Field data were collected during 2007 and 2008 from twelve study sites along the Santa Cruz River and nine study sites along the San Pedro River in southern Arizona. The twelve effluent-dominated sites were apportioned into two effluent-dominated reaches: the shallow-groundwater upper Santa Cruz reach which receives its effluent input from the Nogales International Wastewater Treatment Plant (NIWWTP) and the deep-groundwater lower Santa Cruz River downstream (north) from Roger and Ina Roads Wastewater Treatment Facilities in Tucson, Arizona. In the upper Santa Cruz reach, two of the 12 sites were located five and ten kilometers upstream of the NIWWTP to serve as within-river, non-effluent controls. Downstream of the NIWWTP, five sites were situated within a 55-kilometer effluent-dominated reach to capture changing flow conditions with increasing distance from the point of discharge. Similarly, five sites were established along a 60-kilometer effluent-dominated reach in the lower Santa Cruz to capture a gradient of flow intermittency downstream from the Roger and Ina Roads Wastewater Treatment Facilities. Nine sites, inclusive of perennial, intermittent and ephemeral flows, were located along the San Pedro River, a less urbanized, non-effluent control river (Figure 38; Table XX).

Study Area: effluent-dominated Santa Cruz River

The Santa Cruz River originates in the San Rafael Valley, and initially flows south into Mexico following a 50-kilometer loop in which it turns northward and re-enters Arizona approximately eight kilometers east of Nogales. From the international border, the Santa Cruz River continues northward for 170 kilometers to the confluence of the Gila River (ADWR, 1999a; Figure 38). Historically, flow was perennial from its headwaters to near the town of Tubac, Arizona, approximately 65 kilometers north of the U.S./Mexico border. Downstream of Tubac, the river was characterized by intermittent and ephemeral reaches to its confluence with the Gila River (Tellman *et al.*, 1997). Today, the portion of the river that flows north in the U.S. can be divided into two effluent-dominated reaches, identified here as the upper and lower Santa Cruz River.

The upper Santa Cruz is a bi-national river flowing through the rapidly growing urban areas that encompass Nogales, Sonora (Mexico) and Nogales, Arizona. Characterized by mild winter temperatures and high summer temperatures, the region is distinguished by a bimodal precipitation regime, with convective thunderstorms creating summer monsoon rains and Pacific frontal storms providing precipitation in winter (Adams and Comrie, 1997). Average annual precipitation recorded at Tumacácori between 1948 and 2009 was approximately 40 cm.

The floodplain aquifer of the upper Santa Cruz reach is characterized by a series of shallow and undulating micro-basins (Nelson, 2007; Villarreal, 2010). Flows are driven by surface runoff, groundwater discharge, and effluent from the NIWWTP, which is released approximately 21 kilometers north of the U.S./Mexico border at the confluence of Sonoita Creek and the upper Santa Cruz. The NIWWTP treats wastewater from Nogales, Arizona and surrounding communities, as well as wastewater from Nogales, Sonora. Perennial, effluent-dominated flow extends from the NIWWTP outfall approximately 50 kilometers north beyond Tubac, Arizona where surface flow intermittency increases. Release of treated wastewater into the river began in 1951, and in 1972 the facility was upgraded and renamed the Nogales International Wastewater Treatment Plant (IBWC, 2005). In 1992 major upgrades to the treatment plant were completed, giving it a capacity of 17.2 million gallons per day (mgd) (AWWQRP, 2002). Technology upgrades in 2009 led to increased removal of nitrogen compounds and improvement of overall quality of the discharged water (IBWC, 2010). For the 2007 and 2008 study years, mean annual flow at the USGS Nogales gage located approximately 15 kilometers upstream of the NIWWTP (USGS #09480500) was 0.195 m^3s^{-1} and 0.087 m^3s^{-1}. Within the effluent-dominated reach of the upper Santa Cruz River, mean annual flow at the Tubac gage (USGS #09481740) for study years 2007 and 2008 was 0.87 m^3s^{-1} and 0.78 m^3s^{-1}.

The lower Santa Cruz reach begins in the Tucson metropolitan region, and extends downstream to the confluence with the Gila River. Similar to the upper basin, a bimodal precipitation regime drives flow dynamics and annual precipitation averaged from 1948-2009 was 37 cm. Prior to the onset of European settlement, the lower Santa Cruz River was a shallow stream occupying a broad, flat floodplain covered with mature mesquite forests and cottonwood trees (Johnson and Haight, 1981). Flows were historically variable and highly dependent on season. By the early 20th century, flows were becoming increasingly intermittent in many areas due to groundwater pumping for agricultural practice and urban development.

Today, the floodplain of the lower Santa Cruz is narrow, incised and often scoured from flooding (PCFD, 2005). Growth patterns have continued to lower the water table to over 50 meters below the surface (AWWQRP, 2004). Perennial flows are sustained by daily effluent discharge from the Roger Road Wastewater Treatment Plant (WWTP) and Ina Road Wastewater Reclamation Facility (WRF), which release more than 50 million gallons per day (mgd) of treated wastewater into the river channel, supporting a narrow band of *Salix*-dominated forest for over 50 kilometers downstream. Mean annual flow at Cortaro gage (USGS # 09486500) measured 2.27 m^3s^{-1} and 2.08 m^3s^{-1} for study years 2007 and 2008. This gage is located approximately 10 kilometers downstream from Roger Road outfall.

Study Area: non-effluent San Pedro River

The San Pedro River is an interrupted perennial river that flows northward from its headwaters in Sonora, Mexico through the Chihuahuan and Sonoran deserts to its confluence with the Gila River. Stream flow varies widely among years; the alluvial aquifer is recharged by flood flows from rainstorms and by groundwater inflow from the regional aquifer. Surface flow duration and depth to groundwater vary along the length of the river due to geologic differences in depth to bedrock, proximity to tributaries, and groundwater pumping from agricultural and municipal use. In some areas, water availability in the riparian zone has fallen below threshold levels needed to sustain *Populus-Salix* forests and emergent wetlands (Lite and Stromberg, 2005; Stromberg *et al.*, 2005). In these reaches, stream channels are wide and dry, supporting little herbaceous vegetation with *Tamarix* shrublands as the predominant woody cover.

Based on geomorphic differences, the river is divided into two basins within the San Pedro River watershed (Tuan, 1962). The upper basin extends from its headwaters (elevation 1500 m) to a geologic constriction known as the

Narrows (elevation 1000 m) and the lower basin extends from the Narrows to the confluence with the Gila River (elevation 580 m). In the upper basin of the San Pedro River, mean annual flow at Charleston (USGS #09471000) for study years 2007 and 2008 was 1.01 m^3s^{-1} and 0.97 m^3s^{-1}. The gage near Redington Bridge (USGS # 09472050) measured mean annual flow in 2007 and 2008 as 0.54 m^3s^{-1} and 0.69 m^3s^{-1} for the lower San Pedro basin.

GIS and aerial photo analysis

To quantify changes in vegetation patch types for the twelve study sites on the effluent-dominated Santa Cruz and 9 study sites on the San Pedro River, we analyzed historic aerial photographs from the 1950s through 2010. While methods for establishing historical vegetation conditions are numerous and vary according to time scale and questions being addressed (Swetnam *et al.*, 1999), repeat historical photographs cover a relatively short timeframe and contain a large amount of visual detail and information. Therefore, we used repeat small-scale aerial photographs, which were digitized, georeferenced, and imported into GIS to quantify spatial characteristics of vegetation change.

Early historic aerials (1935) were obtained from the Arizona State University Map Library and scanned at 700 dpi. For images through the mid 1990s, digital scans were obtained from various federal and state agencies (USGS, USDA, ADOT). Scanned photographs were georeferenced in ArcMap using spatially referenced Digital Orthorphoto Quarter Quads (DOQQs) as base maps. We identified up to 50 control points (e.g., road intersections, building corners) per image and used 2nd or 3rd order polynomial transformations to convert scanned photographs to approximate rectified orthoimages, with a root mean square error of less than 4 for all photographs.

Hydrogeomorphic zones. Polygons were drawn on historic aerial images at a scale of 1:5000 to differentiate between hydrogeomorphic zones (terrace, floodplain, channel). Using the 1935 historic aerials which often pre-date theconversion of riparian lands to farm or other land uses, a static boundary between the riparian zone and adjacent uplands was delineated based on visual differences in vegetation and topography. Due to low resolution, we also used the 1955 aerial images to improve the accuracy of georeferencing. Aerial photo analysis and digital elevation maps derived from LIDAR data (Farid *et al.*, 2006) were used to derive a boundary between the river terraces and the active floodplain (Stromberg *et al.*, 2010). Because floodplain boundaries are more dynamic, they were recreated for every photo year based on topographic and vegetation differences detected on the photos. The active channel was delineated as the zone of bare sediments adjacent to the low-flow channel, and the low-flow channel was identified by presence of surface water. For intermittent-flow reaches, the most recently visible scoured channel thread was delineated as the low-flow channel.

Riparian cover types. To map cover types, polygons were drawn around homogeneous vegetation patches while viewing the images at a scale of1:3000. A minimum polygon size was established at 2,500 square meters (50 m x 50 m) and within each polygon, percent cover of vegetation type was visually estimated using cover classes of 0, 1–5%, 6–20%, 21–40%, 41–60%, 61–80% and 81–100%. Two investigators (M. Tluczek and M. White) performed all photographic analysis and polygon data were cross-referenced and inspected for error. 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 (Stromberg et. al, 2010). Six cover types emerged as distinguishable when comparing DOQQ aerial imagery with field data collected on both rivers (Table XXI). Mature *Populus fremontii* and *Salix gooddingii* trees were identifiable on photographs by their height, broad-leaved foliage, and large canopy. All other woody vegetation was classified as woodland-shrubland (woody other) and 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). Herbaceous patches were delineated from bare ground based on color and texture, but estimates of change have high uncertainty given that annual plant cover varies seasonally and each photo series was flown in a different month. Bare ground included sediments in the active channel and unvegetated areas of the floodplain and terrace. Areas for each patch type within a stream reach were calculated by summing products of the cover class midpoint for each polygon and a polygon's relative area in the reach.

Temporal and spatial changes in patches. To assess temporal changes in patch types, a cover type table was generated by establishing a lattice of grid points for each of the 12 1-km sites on the Santa Cruz and for the 9 1-km sites on the San Pedro River in ArcMap. We classified each point by the predominant cover type within its polygon and values were tabulated for every photo year sampled. We then calculated values 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 to capture changes by decade.

Field data collection

Field data were collected during 2007 and 2008 from twelve study sites along the Santa Cruz River and nine study sites along the San Pedro River in southern Arizona. Sites were selected to capture a range of hydrologic conditions along both rivers to include intermittent and perennial flow reaches. At each site, two transects were established that extended perpendicular to the river on both sides, from the edge of the low-flow channel to the edge of the *Prosopis* – *Sporobolus* (mesquite-sacaton) terraces. This zone encompassed the active channel bars and the floodplain, which includes fluvial surfaces built of sediments deposited in the present regime of the river (Graf 1988).

Vegetation patch types along the two transects at each site were classified based on physiognomy and floristics, following rules developed for the National Vegetation Classification system (Grossman *et al.*, 1998). Physiognomic classes included forest (canopy layer >60% cover), woodland (canopy 25–60%), shrubland (canopy <25% and mid-stratum >25%), grass- or forbland (canopy and mid-stratum <25% and groundcover >25%), and open (cover in all three strata <25%). Patch types were further divided based on composition and stem size class of the dominant woody species. Cottonwood-willow woodlands and forests were combined into one woodland-forest type, and three broad age classes were recognized: Young stands (maximum stem diameters <20 cm, which equates to age <10 years based on equations that relate stem diameter to tree age (Stromberg, 1998a), mature (stems 20-90 cm, age ca. 10-50 years), and old (stems >90 cm, age >50 years).

Due to substantial differences in floodplain widths between river settings, vegetation plots were sampled at one transect per site on the San Pedro River and on both transects on the Santa Cruz River. Study plots were 5 x 20 m (long axis parallel to the river) and randomly stratified within each discrete patch. The number of plots sampled varied among sites depending on floodplain width and number of patch types. If patches were wider than 25 m, another plot was added for each additional 25 m of that patch (i.e., 2 plots for patches 26–50 m wide). Within each study plot, data were collected on abundance and stem size structure for all woody species.

Vegetation abundance measures were collected by species, and included canopy cover, stem density, and basal area. Canopy cover was measured at two spots per plot using a spherical densiometer, and the average of those measurements were calculated. Stem density was calculated by counting each live tree and shrub stem emerging from the ground in the study plots, and basal diameter of each stem was measured using a diameter tape or calipers. Abundance data were reduced to the site level by weighting the plot-level values by the percent of the floodplain occupied by the respective patches.

Species were placed into functional groups as a method of collapsing phylogenetic data into ecological groupings. Species within a functional group respond similarly to disturbance and resource availability (Tabacchi *et al.*, 1996). Species were divided into five functional groups (Table XXII; Grime, 1977) based on water stress tolerances, response to disturbance and life history characteristics as described in the USDA PLANTS National Database (USDA-NRCS, 2011) and the USFS Fire Effects Information Systems (http://www.fs.fed.us/database/feis/).

Data analysis

Woody stem density, basal area, and canopy cover were compared between river settings with nonparametric Kruskal-Wallis tests, as assumptions of normality and variance were difficult to consistently satisfy. When the Kruskal-Wallis showed that significant difference existed between treatments, a post-hoc, nonparametric multiple comparison test was employed (Bonferroni), as described in Zar (1984). Nonparametric Kruskal-Wallis tests were also used for lateral analysis as sample sizes were low and unequal, and assumptions of normality were difficult to consistently satisfy. Longitudinal patterns were analyzed with Pearson correlation analysis. All analyses were conducted in PASW 18 (SPSS, Inc. 2011).

RESULTS

Historic and present vegetation patterns

Following the establishment of the NIWWTP in 1972, effluent subsidy in the shallow-groundwater upper Santa Cruz reach has supported patches of woody vegetation, while woody vegetation upstream of the facility has steadily declined. Another major event that has shaped the vegetation during this time period was the powerful 1983 flood event, which is bracketed by our photo datasets 1975 and 1984. Representative transition matrices for each site are presented to illustrate vegetation dynamics between 1955 and 2010.

Woody vegetation at two non-effluent sites upstream of the NIWWTP declined in the upper Santa Cruz reach from 1955 to 2010. At the site furthest upstream, 50% of *Populus-Salix* forest shifted to bare ground and 50% to other woodland vegetation, while 17% of the woody vegetation at the upstream site closest to the treatment facility arose from former *Populus-Salix* forest (Figure 39; Table XXIII). There was a slight increase in woody cover in the decade following the 1983 flood at both sites, followed by a decrease leading to less than 10% woody vegetation in 2010. The floodplains of both sites were predominantly herbaceous and open cover types in 2010.

The effluent-dominated reach downstream of the NIWWTP supported

Populus-Salix forest for approximately 25 kilometers. In general, woody vegetation declines considerably with increasing distance downstream from the NIWWTP. At the sites 15 and 25 km downstream (Santa Gertudis and Chavez Siding, respectively) woody vegetation occupied more than 40% of the floodplain throughout 1955 – 2010, with the exception of the 1983/4 flood years. Since 1983 woody vegetation has increased at Santa Gertudis, with over 80% of the floodplain supporting woody vegetation in 2010, 60% of which was *Populus-Salix* forest. Chavez Siding supported <10% *Populus-Salix* forest in 2010, and had approximately 40% woody cover since the 1983 flood. Further downstream as surface flow becomes increasingly intermittent, vegetation shifts to herbaceous cover or open ground. Between 35 km (Amado) and 55 km (Sahuarita) downstream, herbaceous and open patch categories comprised more than 70% of the 2010 floodplain on average, with no forest cover and less than 20% identified as woody vegetation. Two sites (Continental, 45 km and Sahuarita, 55 km) are outside the influence of effluent subsidy, and woody cover declined from over 40% in the 1950s to less than 15% of the floodplain in 2010. At these sites, herbaceous and open patches comprise over 70% of the 2010 floodplain (Figure 39; Table XXIII).

Vegetation patterns in the deep-groundwater lower Santa Cruz reach are vastly different from the upper reach. Woody vegetation, particularly *Populus-Salix* forest, comprises much less of the floodplain (Figure 40; Table XXIV). Woody cover in this reach is largely dominated by shrubland-woodland comprised of young *Salix goodingii, Hymnoclea sp.* and *Baccharis sp*. At Ina Road, the site closest to the closest to the Roger and Ina Roads WWTPs, less than 20% of the 2010 floodplain was comprised of woody vegetation, with approximately 10% *Populus-Salix* forest (Figure 40). Between 1955 and 2010, *Populus-Salix* forest was replaced by herbaceous and open categories, which comprised over 60% of the floodplain from 1983 through 2010. Further downstream at Avra Valley Road (15 km) there were no significant changes in vegetation patterns from 1955 – 2010, with more than 50% of the floodplain occupied by herbaceous vegetation or bare ground. Just over 10% of the 2010 floodplain supported woody vegetation, and was predominantly *Hymnoclea sp.* and *Baccharis sp*. At Hardin Road (30 km downstream), woody vegetation has comprised approximately 40% of the floodplain from 1955 – 2010, and since 1983 composition has shifted with *Populus-Salix* forest covering nearly 20% of the floodplain in 2010 (Figure 40; Table XXIV). At Sasco Road (45 km) woody vegetation mapped in 1955 shifted by 11% and 22% in 2010 to herbaceous and bare ground, respectively. Woody vegetation is comprised of mainly shrublands with *Prosopis sp.* and *Hymonoclea sp.* and covers nearly 60% of the 2010 floodplain. Woody vegetation at the site furthest downstream (55 km) remained low (<40%) between 1955 and 2010. In the 2010 floodplain, over 20% of the floodplain 55 km downstream was identified as *Populus-Salix* forest and field verified as a narrow band of *Salix* immediately adjacent to the low flow channel and subsidized by agricultural irrigation run-off.

On the non-effluent San Pedro River, perennial sites supported the highest percentages of *Populus-Salix* forest area. In the upper basin (n = 5; Figure 4) the percentage of floodplain area occupied by woody vegetation increased from 1955 – 2005, with a slight decrease from 2005 to 2010 (Figure 41). *Populus-Salix* forest expanded by 78% in the floodplain of the perennial Lewis Springs site from1955 to 2010 (Table XXV). Woody vegetation dominated floodplains of intermittent sites, with the driest site in the upper basin ephemeral sites (Narrows) supporting no *Populus-Salix* forest area, but with approximately 60% woody vegetation cover in 2010. Patterns were similar in the lower basin of the San Pedro River (n = 4, Figure 42; Table XXVI), with perennial sites supporting the highest percentage of *Populus-Salix* forest. Woody vegetation comprised approximately 60% of the floodplain of the driest site in this basin (H&E 3), with no *Populus-Salix* forest area (Table XXVI). There was more change over time in the types of vegetation cover in the lower basin, with shrublands-woodlands arose primarily from preexisting shrubland-woodland, bare ground or grassland.

Vegetation composition and structure in effluent and non-effluent systems

Site composition by patch types. Field data supported analyses of the aerial photographs. At the two intermittent sites upstream of NIWWTP, herbaceous and shrubland patches comprised of over 75% of the floodplain, and no *Populus-Salix* forest occurred (Table XXVII; Figure 43). Downstream of the NIWWTP, in the shallow groundwater, effluent-dominated portion of the upper Santa Cruz, woody vegetation declined with increasing distance downstream. The two site closest to the effluent release point supported more than 80% and 30% *Populus-Salix* forest, respectively while downstream sites outside the influence of effluent had little woody vegetation and more than 80% herbaceous and open patches (Table XXVII; Figure 43).

Patterns in the deep groundwater, lower Santa Cruz were considerably different from the upper reach. In this system, woody vegetation increased with increasing distance downstream (Table XXVII; Figure 44). At the two sites closest to the effluent input (8 km and 15 km) woody vegetation, including the shrubland category, occupied less than 20% of the floodplain. At the site sampled 30 km downstream, woody vegetation increased to 30% of the floodplain, 20% of which was *Salix* forest. The two sites furthest downstream (45 and 60 km) supported the most woody vegetation with nearly 40% of both floodplains supporting woodland or shrubland patches (Figure 44).

Landscape heterogeneity (number of patch types) was highest on the San Pedro River, a non-effluent control. *Populus-Salix* forest occurred at six out of nine sites (67%), and comprised from 25% to over 50% of the perennial site floodplains (Table XXVIII; Figure 45). The intermittent and ephemeral sites were mainly comprised of woodland and shrubland patches, which averaged approximately 65% of the floodplains of these sites (n=6).

Species richness and functional groups. Eighteen species (two identified only to genus) of woody plants were identified in the upper and lower Santa Cruz River reaches. Nineteen species) were present on the control river (Table XXII). Sixteen species were common to both systems. With respect to functional group distribution, the effluent-dominated portion of the upper Santa Cruz reach had high percentages (>20%) of species occurrences in hydric pioneer, xeromesic pioneer, and xeromesic non-pioneer functional groups, with hydric pioneers (e.g., *Populus fremontii*) as dominant (Table XXII). Vegetation patterns in the lower Santa Cruz reach followed similar trends, but dominance shifted toward the xeromesic functional group (e.g., *Tamarix* and *Prosopis*) and hydric pioneers were largely represented by *Salix gooddingii* (Table XXIX). The upper and lower basins of the San Pedro River had high percentages (>20%) of species occurrences in hydric pioneer, xeromesic pioneer, and xeromesic non-pioneer functional groups. Hydric pioneer species dominated perennial sites (*Populus* *fremontii, Salix gooddingii)* while intermittent sites had higher occurrences of xeromesic groups including *Tamarix and Prosopis* (Table XXX).

Vegetation abundance. In all three river settings, the hydric pioneer functional group had the highest basal area (Figure 46; Tables XXXI & XXXII). On the Upper Santa Cruz and San Pedro Rivers, the basal area was derived by fewer large stemmed species (*Populus fremonti, Salix gooddingii)* whereas on the lower Santa Cruz the abundant stems of smaller woody species *(e.g., Baccharis salicifolia)* accounts for the high basal area in this category (Figures 46 & 47). Stem density and basal area were significantly higher at the perennial flow sites of the Santa Cruz River. The San Pedro River was more heterogeneous, with some intermittent sites having higher stem densities than perennial (Figure 47; Tables XXXII & XXXIV).

Basal area and stem density of the perennial sites (n = 3) did not differ significantly between perennial sites of the upper and lower Santa Cruz River and San Pedro Rivers (Figure 48). However, the highest recorded basal area occurred at perennial sites in the shallow-groundwater upper Santa Cruz and the lowest were in the deep groundwater lower Santa Cruz. Although not significantly different, stem densities were greater at perennial sites of the effluent-dominated reaches, with *B. salicifolia* and *H. monogyra* as the primary species contributing to this difference. There were significant differences in canopy cover at the perennial sites among the three settings (H=7.547, 2 d.f., P = 0.023). Canopy cover did not differ between the upper Santa Cruz and the San Pedro Rivers, but both of these had greater canopy than at the Lower Santa Cruz reach (USC-LSC, P<0.05; SP-LSC, P<0.05; Figure 48).

Longitudinal trends within an effluent-dominated system

In the upper Santa Cruz River, basal area and canopy cover declined significantly with increasing downstream distance as indicated by correlation analysis (basal area: Pearson's = -.880, P = 0.048; canopy cover: Pearson's = -.893, P = 0.041; Figures 46 & 49; Table XXXI). Hydric species, specifically *Populus* and *Salix,* comprised the majority of the basal area and canopy cover in this reach. There was a shift toward xeromesic functional groups approximately 35 km downstream of the NIWWTP. Stem density patterns were a little less clear and there was no significant correlation with increasing distance. However, stem densities were highest at the site closest to the NIWWTP and at the 35 km downstream point (Figures 47 & 49). Hydric species (*Populus* and *Salix*) comprised the majority of stems closest to the point of effluent release, and at the 35 km point, xeromesic species (*Hymonoclea, Tamarix)* became more abundant. Importance values also reflected this dynamic, as numbers shifted from 66% for hydric pioneer 15 km downstream to 71% for xeric pioneers 55 km downstream (Table XXXI).

In the lower Santa Cruz reach, there were no significant correlations between increasing downstream distance and woody vegetation abundance metrics (basal area, stem density, canopy cover), although there was a pattern of increasing woody vegetation with increased distance. Hydric species, specifically *S. gooddingii* and *B. salicifolia,* comprised the majority of the basal area and stem densities at these sites. There was a shift in functional groups toward more xeromesic species with increasing distance downstream (Figures 46 & 47). Calculated importance values support this pattern, as hydric pioneers had higher scores at sites closer to the treatment facilities and xeromesic functional groups had higher scores further downstream (Table XXXI). Canopy cover was low at sites both near and far from the point of effluent introduction, and highest at the site 30 km downstream (Figure 49).

Lateral trends in an effluent-dominated floodplain

In the upper and lower reaches of the effluent-dominated Santa Cruz near-channel zones supported the highest stem densities (Figures 50 and 51). The San Pedro River had more evenly distributed stem densities across floodplain zones regardless of site hydrology. Similarly, in the control reach of the Santa Cruz River upstream of the NIWWTP, there were no significant differences in woody stem densities between near (<25 m) and far (>25 m) floodplain zones.

Within the effluent-dominated upper Santa Cruz reach, the site located 15 km downstream from the NIWWTP (Santa Gertudis) *Populus* and *Salix* stems occurred in both both near and far floodplain zones, with highest densities within 25 m of the channel. Differences were significant in other woody vegetation stems, comprised mainly of *Celtis* and *Fraxinus (*H= 8.221, P[small] = 0.04). At Chavez Siding (25 km), *Populus* and *Salix* stem densities were significantly higher in the near channel zone (H=3.844, P[small] = 0.05; H = 4.436, P[med] = 0.02), while other woody vegetation was significant higher in the far floodplain zone (H=2.852, P[small] = 0.05). Further downstream at Amado (35 km) where flow becomes increasingly intermittent, there were significantly more *Populus* and *Salix* stems in the near channel zone (H = 3,832, P[med] = 0.05; Figure 50). Stem densities of other woody vegetation (*Hymonoclea* and *Tamarix*) were far greater at this site, but differences were not significant by zones. The two furthest downstream sites (45 and 55 km) had no *Populus* and *Salix* stems and no significant differences of the other woody stems across the floodplain.

In the lower reach of the effluent-dominated Santa Cruz, there were no significant differences in *Populus* and *Salix* stems between near and far channel zones at Ina Road (8 km), but other woody vegetation stem densities were significantly higher in the far floodplain (H = 3.23, P[small] = 0.05; Figure 51). At Avra Valley (15 km), there were no significant differences in either *Populus* and *Salix* or other woody vegetation across the floodplain (Figure 51). There were no significant differences between near and far floodplain *Populus* and *Salix* or woody other stem densities at Hardin Road (30 km), although densities were highest in the near channel zone for both groups (Figure 51). Other woody stem densities were significantly higher in the near floodplain zone Sasco Road (45 km) (H= 5.534, P[small] = 0.019; Figure 51). At Wheeler (60 km) *Populus* and *Salix stem* densities were significantly higher in the near channel zone (H =5.369, P[small] = 0.02; Figure 51).

For the San Pedro River, Three Links Farm #1, a perennial flow site in the upper basin, was representative of perennial flow sites. At this site type, there were no significant differences in *Populus* and *Salix* stem densities between near and far floodplain zones, but other woody stems were significantly denser in the far floodplain (H = 4.545, P[small] = 0.033; Figure 52). Three Links Farm #3, representative of an intermittent site, had significant differences in both *Populus* and *Salix* stem densities and other woody stem densities, with higher densities in the near floodplain zone (H = 3.868, P[med] = 0.049; H = 4.083, P[small] = 0.04). At the Narrows, one of two ephemeral sites on the San Pedro, there were no *Populus* and *Salix* stems in the floodplain and no significant differences between the near and far floodplain for other woody vegetation stems.

DISCUSSION

This investigation revealed differences in woody vegetation and community structure between effluent-dominated and non-effluent rivers in the semi-arid southwestern United States. By combining field data with historic aerial analysis, we were able to identify how release of effluent into the Santa Cruz River corridor since the 1970s has affected the distribution, composition and amount of riparian vegetation, and how this response varies depending on hydrologic setting. In both deep-ground water and shallow-groundwater settings, there were sharp contrasts upstream and downstream of the effluent discharge point, with riparian vegetation upstream either absent or in a state of decline. Distinct zonal patterns were apparent with increasing distance from the perennial effluent in the low flow channel, particularly in reaches with greater depth to groundwater. By contrasting the Santa Cruz with a reference river, the San Pedro, we were able to determine that discharge of effluent into the shallow-water table section of the Upper Santa Cruz is maintaining a riparian ecosystem, at least for several kilometers, that resembles the control river with respect to woody species richness and composition of the dominant functional group.

Temporal changes in woody vegetation along effluent-dominated and non-effluent rivers

Temporal changes in vegetation patterns in both effluent-dominated reaches, upstream of the NIWWTP, and along the San Pedro River reflect base flow dynamics and flood disturbance regimes. For both river systems, a large flood event in 1983/4 scoured floodplains and set in motion changes in riparian forest dynamics. Bare soils were exposed following this event that allowed for pioneer trees including *Populus* and *Salix* to establish (Stromberg *et al.*, 2010).

Vegetation dynamics also have been influenced by larger historical flood events (Stromberg *et al.*, 2010). The pioneer vegetation that has established after flooding on the San Pedro differs spatially between *Populus/Salix* (wetter reaches) and *Tamarix* (drier reaches), depending on local extent of stream diversion and groundwater pumping to sustain urban and agricultural land uses (Kingsford, 2000; Fitzhugh and Richter, 2004).

The upper and lower Santa Cruz reaches experienced similar groundwater withdrawals and subsequent declines in surface flow due to increasing demands for freshwater in Nogales and Tucson (AWWQRP, 2002). On this system, effluent subsidies from those same urban centers have established perennial surface flow since the 1970s in both the upper and lower reaches. Vegetation dynamics on the Santa Cruz have varied through time, particularly on the lower Santa Cruz, but support more woody vegetation since the introduction of effluent in the 1970s through 2010.

Vegetation composition and structure in effluent and non-effluent systems

Species richness and functional groups. Only slight differences existed in overall species richness between the three river types, although the contribution to this richness varied with more xeric species in effluent-dominated reaches, especially the deep-groundwater lower Santa Cruz. There also were pronounced differences in functional groups. Xeromesic and xeric functional groups had higher importance values on the effluent-dominated reaches and appeared at the majority of sites sampled. These groups were especially prevalent throughout the deep-groundwater lower reach and at sites further downstream in upper Santa Cruz beyond the influence of the effluent recharge. The hydric pioneer functional group was dominant at sites with perennial flow in effluent-dominated and non-effluent systems. In the shallow groundwater upper Santa Cruz reach and at perennial sites on the San Pedro, *Populus fremontii* and *Salix gooddingii* were the predominant hydric species while in the deep-groundwater lower Santa Cruz *Baccharis salicifolia* and young *Salix gooddingii* prevailed. In the Lower Santa Cruz, conditions limit recruitment of these hydric species to a narrow zone along the effluent channel, allowing the floodplain to be colonized by drought tolerant species not dependent on shallow groundwater or high soil moisture such as *Hymenoclea monogyra* (Stromberg *et al.*, 2005). Despite the effluent subsidy, the long-term effects of groundwater pumping in the lower reach is limiting recruitment or survivorship of *P. fremontii* and *S. gooddingii* (Horton *et al.,* 2001; Lite & Stromberg, 2005) especially further out in the floodplain where the effluent subsidy has little to no effect. These findings are consistent with the idea that along arid region rivers, irregular water availability exerts more of an influence on woody plant richness and diversity than does disturbance (Hupp and Osterkamp, 1996; Tabacchi *et al.*, 1996).

Vegetation abundance. When comparing perennial sites in all three systems, the effluent-dominated upper Santa Cruz and the San Pedro River had higher basal area, stem density and cover than the lower Santa Cruz reach. Hydric species comprised the majority of basal area and stem densities at perennial flow sites, with these numbers on lower Santa were due to primarily to *Baccharis salicifolia* and young *Salix gooddingii* rooted immediately adjacent to the surface flows. It appears the continuous flow of effluent plays a critical factor in sustaining obligate riparian forest communities on the Santa Cruz River, supporting similar findings for other semi-arid riparian ecosystems (Stromberg, 1993b; Tickner *et al.*, 2001; Marler, 2005). Vegetation patterns along effluent-dominated systems, however, are reflective of “top down” hydrology, where surface flows are sustained even in losing reaches. Water quality differences also cannot be overlooked when comparing effluent-dominated to non-effluent systems, as changes in nutrient availability, specifically increased nitrogen concentration may play a role in improving seedling survivorship (Adair & Binkley, 2002), but appears to have limited influence on growth rates of *P. fremontii* and *S. gooddingii* (Marler *et al.*, 2001).

Longitudinal trends within an effluent-dominated system

One key management question is how much riparian habitat can be sustained by effluent discharge and how hydrogeomorphic conditions may influence response. On both reaches of the Santa Cruz, longitudinal extents of woody vegetation along the stream channel were somewhat similar (40 km downstream from the NIWWTP when surface flows dissipate completely, and 55 km downstream from Roger and Ina WWTPs). Surprisingly, hydric species were sustained for greater lengths in the deep-groundwater lower reach, but greater effluent volumes, channelization, and agricultural runoff help to explain this difference. In the lower reach, nearly three times the volume of effluent is released into the channel, and flows extend for more than 50 km downstream. However, run-off from adjacent agricultural lands supplements this surface flow, which may explain the vegetation patterns. In both systems, vegetation patterns appears to indicate that water quantity may be more critical than water quality in the development of maintenance of a structurally diverse riparian ecosystem.

There have been changes through time in the length of the riparian forests. In the upper reach, flows extended 40 km downstream until 2009, when a technology upgrade improving the quality of wastewater has increased infiltration downstream. Current data show that perennial effluent extends approximately 20 km downstream (FOSCR, 2010). On the upper reach of the Santa Cruz, effluent subsidy has maintained significant *Populus-Salix* forest for approximately 25 km downstream. In spring 2005, however, sudden mortality of *Populus fremontii* and *Salix gooddingii* species were documented along the upper reach. Aerial photographs and satellite imagery from the previous year did not indicate that the riparian vegetation was exhibiting typical physical responses to drought or groundwater decline (Villarreal, 2010), such as canopy die-back or leaf senescence (Rood *et al.* 2000, Amlin and Rood 2003, Pearce *et al.* 2006). Given the absence of typical drought response signals, the die-off event in 2005 appeared suddenly and may suggest a threshold change in vegetation composition (Villarreal, 2010). Further downstream, floodplains have remained more homogeneous, comprised of mainly herbaceous and open patch types, with limited woody vegetation supported at Amado Road (35 km). Amado once received effluent subsidy and now largely falls outside the influence of effluent, which may lead to a further decline in woody vegetation.

Basal area and canopy cover were significantly higher closer to the NIWWTP In the shallow-groundwater upper reach. The floodplain at our first site supported an expansive *Populus-Salix* forest with stem sizes ranging from 10 - 42 cm. However, *Populus-Salix* forest was sparse at the next site downstream (25 km) and disappeared altogether even further downstream. Stem density patterns were less linear, but reflective of shifts in functional groups as densities of xeromesic species, such as *Hymenoclea* and *Tamarix*, increased with downstream distance and increasing flow intermittency.

The deep-groundwater, lower reach had higher basal area, stem densities and canopy cover at middle distances downstream. The site immediately downstream of the Ina WWTP outfall is channelized and has limited floodplain area for the woody vegetation to develop. With increasing distance, the floodplain widens and opportunities for woody species to establish increase, as reflected by the data. In the lower reach, only *Salix* was the dominant hydric pioneer, with very little *Populus* occurring.

Lateral trends in an effluent-dominated floodplain

Many factors co-vary along lateral floodplain gradients, and untangling their effects can be challenging. However, zonation patterns for stem density and size class across the floodplain of the effluent-dominated reaches were much more pronounced than in the floodplain of the control river. In the non-effluent San Pedro River, a mosaic of woody vegetation and size classes were distributed across the floodplain, with plant community patterns reflecting individual species tolerance to depth to groundwater, flood intensity, and geomorphic surfaces (Lite *et. al*, 2005; Stromberg *et. al*, 2008).

Across the floodplains of the effluent-dominated system, stem densities were greater in the near channel zones of both effluent-dominated reaches. In the upper Santa Cruz reach, larger size classes tended to be supported at sites closer to the treatment facility. Zonation patterns and shifts toward more xeroriparian species became more apparent with increasing streamflow intermittency. These zonation patterns were most pronounced in the deep groundwater lower reach of the Santa Cruz, regardless of distance from treatment facility. If any *Populus* and *Salix* stems were supported, they tended to be smaller size classes and within the first 25 meters from the low flow channel.

The far floodplain of this effluent-dominated reach only supported a few woody stems of xeroriparian species, indicating that the disconnection from groundwater significantly impacts woody structure in effluent-dominated systems. These trends indicate that the surface flows from effluent support a narrow band of woody vegetation, but further out in the floodplain patterns are similar to an ephemeral system.

CONCLUSIONS

Anthropogenic alterations to rivers and associated riparian plant communities have grown increasingly evident throughout the southwestern United States, with surface flow diversions, groundwater pumping, and discharge of effluent into stream channels making management and maintenance of river systems increasingly complex. The long-term release of effluent for riparian restoration and management raises important questions about outcomes on riparian ecosystem structure and function. Understanding patterns and distributions of current vegetation in an effluent-dominated system requires at least some elemental understanding of historical vegetation trends and their interactions with anthropogenic and natural disturbance legacies. Long-term perspectives are needed for assessing directional change and forest conservation needs (Stromberg *et al.*, 2010). The combined approach of field-based data collection with historical aerial photo analysis has provided a clearer understanding of these interactions, and may serve as guidance for riparian restoration and conservation in human-altered landscapes.

The Santa Cruz River in southern Arizona has proven an ideal setting in which to study vegetation changes along a system given its varying depths to groundwater and surface flows long-driven by effluent release. Our research has shown that effluent-dominated systems maintain longitudinal patterns driven by the increase in water availability. Underlying hydrologic conditions influence the abundance and composition of woody vegetation floodplain patterns both laterally and longitudinally. These findings are similar to those of Stromberg *et al.* (1993), AWWQRP (2002), Marler (2005), and Villarreal (2010) showing greater development of the vegetation community with perennial effluent flows downstream of a treatment facility. The San Pedro River, one of the few undammed perennial rivers in the southwestern United States, also provided an example of target riparian conditions for restoration and management.

Ultimately, the current lack of understanding about systems receiving effluent underscores the growing need for suitable methods to evaluate ecological dynamics of these systems. Although some biotic and abiotic attributes varied between reaches, the overall picture shows structural and functional similarities in the woody communities established on the control and effluent-dominated reaches. The changes observed in this study indicate that the influence on vegetation may not be directional and is perhaps subject to thresholds mediated by local and regional environmental factors. Insights from temporal and spatial patterns of riparian forest expansion and contraction along effluent-dominated waterways allow managers to develop tools for monitoring and managing other similar systems.

Table XX. Study site information along the Santa Cruz and San Pedro Rivers

		SAN PEDRO RIVER *(Non-effluent control)*				
Site Name	Map Code	Flow Permanence	Elevation (m)		Latitude	Longitude
Lewis Springs	1	perennial	1230		31.555827	-110.139770
Fairbanks	2	intermittent	1166		31.719315	-110.192990
Narrows	3	intermittent	1006		32.135674	-110.289234
Three Links Farm #1	4	perennial	998		32.164181	-110.295619
Three Links Farm #3	5	intermittent	988		32.197852	-110.313022
Spirit Hollow Intermittent	6	intermittent	786		32.576149	-100.515918
Spirit Hollow Perennial	7	formerly perennial	783		32.533110	-110.519229
H&E #3	8	intermittent	689		32.773245	-110.674157
TNC Preserve P	9	perennial	604		32.930766	-110.743122
		SANTA CRUZ RIVER *(Effluent-dominated)*				
				Distance from Outfall (km)		
Santa Fe Ranch	10	intermittent	1092	-10	31.404300	-110.896519
Calabasas	11	intermittent	1070	-5	31.429878	-110.924696
		Nogales International Wastewater Treatment Facility				
Santa Gretudis	12	perennial	995	15	31.561632	-111.046291
Chavez Siding	13	perennial	960	25	31.645824	-111.047550
Amado	14	perennial	936	33	31.703670	-111.054035
Continental	15	intermittent	875	48	31.835892	-110.990138
Sahuarita	16	intermittent	825	60	31.959540	-110.963874
		Roger and Ina Roads Wastewater Treatment Facilities				
Ina	17	perennial	660	8	32.336229	-111.080780
Avra Valley	18	perennial	629	18	32.401843	-111.143707
Hardin	19	perennial	576	38	32.480063	-111.322608
Sasco	20	intermittent	549	48	32.544830	-111.406742
Wheeler	21	intermittent	539	58	32.577608	-111.467493

Table XXI. Patch types mapped along the Santa Cruz and San Pedro Rivers

Cover type	Description
Populus-Salix forest	Mainly mature broadleaf forests of *Populus fremontii* and *Salix gooddingii*.
Woodland-shrubland	On floodplains, primarily *Tamarix* sp. and *Prosopis velutina*. Also includes smaller shrubs, e.g., *Baccharis* spp., and *Hymenoclea* sp. May also include minor occurrences of *Fraxinus velutina* Torr., *Celtis reticulata* Torr., and younger *Populus* and *Salix sp.* On terraces, primarily *P. velutina* with lesser amounts of *Acacia spp.* and smaller shrubs, notably *Atriplex sp.* and *Ziziphus sp.*
Herbaceous	On floodplains, grasses including *Cynodon dactylon* (L.) Pers., *Sorghum halepense* (L.) Pers and *Sporobolus spp*., and forbs.
Bare ground	Bare sediment (floodplain or channel) or unvegetated soil (terrace)
Agriculture	Active and recently abandoned fields
Urban	Anthropogenic land uses including buildings, roads, railrods, and other infrastructure.

Table XXII. Functional groups of woody species on San Pedro and Santa Cruz Rivers.

SAN PEDRO RIVER

Moisture Requirement	Successional Status	Species	Common Name
Hydric	Pioneer	*Baccharis salicifolia*	Seep Willow
		Populus fremontii	Fremont Cottonwood
		Salix exigua	Coyote Willow
		Salix gooddingii	Gooding Willow
Mesic	Non-pioneer	*Fraxinus velutina*	Velvet Ash
		Celtis reticulata	Boxelder
		Juglans major	Arizona Walnut
Xeromesic	Pioneer	*Baccharis sarothroides*	Desert Broom
		Chilopsis linearis	Desert Willow
		Hymonoclea monogyra	Singlewhorl Burrobrush
		Hymenoclea salsola	White Burrobrush
		Tamarix ramosissima	Salt Cedar
Xeromesic	Non-pioneer	*Parkinsonia sp.*	Paloverde
		Prosopis velutina	Velvet Mesquite
Xeric	Non-pioneer	*Acacia greggii*	Catclaw Acacia
		Atriplex canescens	Fourwing Saltbush
		Larrea tridentata	Creosote Bush
		Lycium sp.	Wolfberry
		Ziziphus obtusifolia	Lotebush

SANTA CRUZ RIVER

Moisture Requirement	Successional Status	Species	Common Name
Hydric	Pioneer	*Baccharis salicifolia*	Seep Willow
		Populus fremontii	Fremont Cottonwood
		Salix exigua	Coyote Willow
		Salix gooddingii	Gooding Willow
Mesic	Non-pioneer	*Fraxinus velutina*	Velvet Ash
		Celtis reticulata	Netleaf Hackberry
		Sambucus nigra	Black Elderberry
		Juglans major	Arizona Walnut
Xeromesic	Pioneer	*Baccharis sarothroides*	Desert Broom
		Chilopsis linearis	Desert Willow
		Hymenoclea monogyra	Single whorl Burrobrush
		Salix taxifolia	Yewleaf Willow
		Tamarix ramosissima	Salt Cedar
Xeromesic	Non-pioneer	*Parkinsonia sp.*	Paloverde
		Prosopis velutina	Velvet Mesquite
Xeric	Non-pioneer	*Acacia greggii*	Catclaw Acacia
		Larrea tridentata	Creosote Bush
		Lycium sp.	Wolfberry

Table XXIII. Cover type origin table. Values indicate the percentage of points mapped in 2010 that arose from cover types as mapped in the 1950s for the floodplain and channel zone and terrace of 1-km sites along the effluent-dominated Upper Santa Cruz River.

			CHANNEL/FLOODPLAIN Patch Types (%)						TERRACE Patch Types (%)					
			Status in 2010						**Status in 2010**					
			Populus Salix	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*	*Populus Salix*	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*
		Status in 1950s												
Santa Fe Ranch	*-10 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	20%	0%	0%	0%	0%
		Woody other	50%	0%	13%	25%	0%	0%	0%	20%	0%	40%	10%	0%
		Herbaceous	0%	0%	50%	0%	0%	0%	0%	60%	100%	40%	80%	100%
		Bare ground	50%	0%	38%	75%	0%	0%	0%	0%	0%	20%	10%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Calabasas	*-5 km*	*Populus/ Salix*	0%	17%	0%	43%	0%	0%	0%	10%	0%	0%	0%	0%
		Woody other	0%	50%	8%	0%	0%	0%	0%	50%	0%	0%	0%	67%
		Herbaceous	0%	33%	17%	29%	100%	0%	0%	40%	0%	0%	100%	33%
		Bare ground	0%	0%	75%	29%	0%	0%	0%	0%	0%	0%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Santa Gertudis	*15 km*	*Populus/ Salix*	38%	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	54%	0%	0%	0%	0%	0%	0%	57%	100%	0%	4%	0%
		Herbaceous	0%	0%	0%	0%	0%	0%	0%	23%	0%	0%	1%	0%
		Bare ground	8%	0%	0%	0%	0%	0%	0%	7%	0%	0%	1%	14%
		Farmland	0%	100%	75%	0%	0%	0%	67%	10%	0%	0%	90%	57%
		Other	0%	0%	0%	0%	0%	0%	33%	3%	0%	0%	3%	29%
Chavez Siding	*25 km*	*Populus/ Salix*	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	0%	25%	0%	0%	0%	0%	86%	20%	20%	0%	0%
		Herbaceous	0%	0%	0%	0%	0%	0%	0%	4%	0%	0%	0%	0%
		Bare ground	65%	0%	25%	100%	0%	0%	0%	7%	10%	20%	10%	0%
		Farmland	33%	0%	50%	0%	0%	0%	0%	4%	60%	60%	86%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	10%	0%	3%	0%
Amado	*35 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	25%	44%	38%	0%	0%	0%	31%	0%	0%	4%	0%
		Herbaceous	0%	25%	11%	15%	0%	0%	0%	2%	0%	9%	0%	0%
		Bare ground	0%	0%	0%	12%	0%	0%	0%	0%	0%	0%	0%	0%
		Farmland	0%	50%	44%	35%	0%	0%	0%	58%	77%	86%	96%	67%
		Other	0%	0%	0%	0%	0%	0%	0%	9%	23%	5%	0%	33%
Continental	*45 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	0%	0%	50%	0%	0%	0%	50%	26%	0%	0%	2%
		Herbaceous	0%	0%	69%	25%	0%	0%	0%	17%	19%	29%	0%	8%
		Bare ground	0%	50%	23%	25%	0%	0%	0%	0%	19%	0%	4%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	33%	26%	43%	91%	84%
		Other	0%	50%	8%	0%	0%	0%	0%	0%	11%	29%	5%	6%
Sahuarita	*55 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	100%	60%	25%	0%	0%	0%	0%	33%	0%	0%	0%
		Herbaceous	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	0%
		Bare ground	0%	0%	30%	0%	0%	100%	0%	0%	0%	0%	0%	0%
		Farmland	0%	0%	0%	75%	0%	0%	0%	0%	67%	71%	98%	0%
		Other	0%	0%	10%	0%	0%	0%	0%	100%	0%	29%	0%	100%

Table XXIV. Cover type origin table. Values indicate the percentage of points mapped in 2010 that arose from cover types as mapped in the 1950s for the floodplain and channel zone and terrace of 1-km sites along the effluent-dominated Lower Santa Cruz River.

			CHANNEL/FLOODPLAIN Patch Types (%)						TERRACE Patch Types (%)					
			Status in 2010						**Status in 2010**					
			Populus Salix	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*	*Populus Salix*	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*
		Status in 1950s												
Ina	*8 km*	*Populus/ Salix*	0%	0%	6%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	50%	28%	0%	0%	0%	0%	0%	16%	60%	0%	81%
		Herbaceous	0%	0%	17%	0%	0%	0%	0%	0%	22%	0%	0%	6%
		Bare ground	100%	50%	50%	100%	0%	0%	0%	0%	6%	20%	0%	13%
		Farmland	0%	0%	0%	0%	0%	0%	0%	50%	9%	20%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Avra Valley	*15 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	100%	27%	25%	0%	0%	0%	29%	25%	41%	3%	25%
		Herbaceous	0%	0%	13%	50%	0%	100%	0%	0%	75%	14%	0%	13%
		Bare ground	0%	0%	53%	25%	0%	0%	0%	14%	0%	23%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	43%	0%	14%	97%	38%
		Other	0%	0%	7%	0%	0%	0%	0%	14%	0%	9%	0%	25%
Hardin	*30 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	0%	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Herbaceous	100%	100%	33%	80%	0%	100%	0%	0%	0%	33%	0%	0%
		Bare ground	0%	0%	33%	20%	0%	0%	0%	0%	100%	33%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	100%	0%	33%	100%	100%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Sasco	*45 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	67%	100%	0%	0%	0%	0%	3%	0%	0%	0%	0%
		Herbaceous	0%	11%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%
		Bare ground	0%	22%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	94%	100%	100%	100%	50%
		Other	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	50%
Wheeler	*60 km*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	17%	0%	0%	0%	0%	0%	0%	50%	0%	7%	0%	0%
		Herbaceous	67%	0%	0%	0%	0%	0%	0%	0%	0%	50%	0%	0%
		Bare ground	17%	0%	0%	100%	0%	0%	0%	50%	0%	43%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table XXV. Cover type origin table. Values indicate the percentage of points mapped in 2010 that arose from cover types as mapped in the 1950s for the floodplain and channel zone and terrace of 1-km sites along the Upper San Pedro River.

			CHANNEL/FLOODPLAIN Patch Types (%)						**TERRACE Patch Types (%)**					
			Status in 2010						**Status in 2010**					
		Status in 1950s	*Populus Salix*	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*	*Populus Salix*	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*
Lewis Springs	*Perennial*	*Populus/ Salix*	0%	0%	14%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	11%	0%	0%	0%	0%	0%	0%	23%	3%	0%	0%	0%
		Herbaceous	11%	0%	14%	0%	0%	0%	0%	27%	79%	0%	100%	0%
		Bare ground	78%	0%	57%	0%	0%	0%	0%	36%	14%	0%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%
		Other	0%	0%	14%	0%	0%	0%	0%	9%	3%	0%	0%	0%
Fairbank	*Intermittent*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	11%	1%	0%	0%	0%	0%
		Woody other	25%	100%	0%	33%	0%	0%	33%	60%	33%	100%	0%	0%
		Herbaceous	0%	0%	0%	33%	0%	0%	11%	7%	0%	0%	0%	0%
		Bare ground	75%	0%	100%	33%	0%	0%	22%	9%	67%	0%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	22%	23%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%
Narrows	*Intermittent*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	44%	0%	60%	0%	0%	0%	86%	0%	17%	0%	0%
		Herbaceous	0%	22%	0%	0%	0%	0%	0%	14%	0%	67%	0%	0%
		Bare ground	0%	33%	0%	40%	0%	0%	0%	0%	0%	17%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
3 Links 1	*Perennial*	*Populus/ Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	20%	64%	40%	25%	83%	0%	0%	87%	82%	0%	77%	100%
		Herbaceous	0%	9%	0%	0%	0%	0%	0%	0%	5%	0%	8%	0%
		Bare ground	80%	27%	60%	75%	17%	0%	0%	8%	14%	100%	8%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	4%	0%	0%	6%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%
3 Links 3	*Intermittent*	*Populus/ Salix*	0%	6%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	19%	0%	0%	0%	0%	0%	68%	89%	64%	57%	50%
		Herbaceous	0%	6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Bare ground	0%	50%	50%	0%	0%	0%	0%	14%	11%	9%	0%	0%
		Farmland	0%	19%	25%	0%	0%	0%	0%	4%	0%	9%	41%	25%
		Other	0%	0%	0%	0%	0%	0%	0%	14%	0%	18%	2%	25%

Table XXVI. Cover type origin table. Values indicate the percentage of points mapped in 2010 that arose from cover types as mapped in the 1950s for the floodplain and channel zone and terrace of 1-km sites along the Lower San Pedro River

			CHANNEL/FLOODPLAIN Patch Types (%)						**TERRACE Patch Types (%)**					
			Status in 2010						**Status in 2010**					
			Populus Salix	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*	*Populus Salix*	*Woody other*	*Herb*	*Bare ground*	*Farm*	*Anthro other*
		Status in 1950s												
Spirit Hollow	*Intermittent*	*Populus/Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	20%	10%	0%	0%	0%	0%	0%	80%	88%	60%	0%	100%
		Herbaceous	20%	60%	22%	100%	0%	0%	0%	10%	13%	40%	0%	0%
		Bare ground	60%	25%	78%	0%	0%	0%	0%	1%	0%	0%	0%	0%
		Farmland	0%	5%	0%	0%	0%	0%	0%	9%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Spirit Hollow	*Perennial*	*Populus/Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	11%	0%	13%	0%	0%	0%	0%	90%	88%	60%	0%	100%
		Herbaceous	28%	47%	27%	33%	0%	0%	0%	9%	13%	40%	0%	0%
		Bare ground	61%	53%	60%	67%	0%	0%	0%	1%	0%	0%	0%	0%
		Farmland	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
HE 3	*Intermittent*	*Populus/Salix*	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	0%	26%	0%	67%	0%	0%	0%	67%	0%	0%	5%	0%
		Herbaceous	0%	0%	0%	0%	0%	0%	0%	13%	0%	0%	0%	0%
		Bare ground	0%	74%	100%	33%	0%	0%	0%	7%	0%	0%	0%	33%
		Farmland	0%	0%	0%	0%	0%	0%	0%	7%	0%	0%	77%	33%
		Other	0%	0%	0%	0%	0%	0%	0%	7%	0%	0%	19%	33%
TNC	*Perennial*	*Populus/Salix*	7%	10%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%
		Woody other	53%	36%	0%	50%	0%	0%	0%	47%	100%	50%	74%	35%
		Herbaceous	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	6%
		Bare ground	0%	36%	0%	0%	0%	0%	0%	27%	0%	17%	0%	24%
		Farmland	33%	12%	0%	0%	0%	0%	0%	17%	0%	33%	21%	18%
		Other	7%	5%	0%	0%	0%	0%	0%	10%	0%	0%	5%	18%

Table XXVII. Summary of Upper and Lower Santa Cruz site characteristics, including floodplain width and patch types. Sites are listed from upstream to downstream.

SANTA CRUZ RIVER *(Effluent-dominated)*						
	Distance from outfall (km)	Transect	Floodplain zone (m)	Patch types	No. of patches	No. of woody plots
Santa Fe Ranch	-10	1	243	O H W S	10	12
		2	210	O H S	7	11
Calabasas	-5	1	207	H W	5	10
		2	307	H S	6	14
Nogales International Wastewater Treatment Facility						
Santa Gretudis	15	1	145	F	2	7
		2	119	O F	3	6
Chavez Siding	25	1	102	H W F	4	4
		2	90	H W	4	5
Amado	33	1	225	O H S W	6	11
		2	212	O H S W	6	11
Continental	48	1	160	O H S	5	7
		2	90	H	2	3
Sahuarita	60	1	84	H S	3	4
		2	80	H S	3	4
Roger and Ina Roads Wastewater Treatment Facilities						
Ina	8	1	191	O H S W	6	9
		2	164	O H S	4	7
Avra Valley	18	1	145	O H S	5	7
		2	135	H W	4	7
Hardin	38	1	163	O H W F	6	9
		2	125	H S F	5	7
Sasco	48	1	115	H S W	3	6
		2	100	H S W	4	5
Wheeler	58	1	105	O H W	4	5
		2	115	O S W	4	6

Patch types = Open (O), Herbaceous (H), Shrubland (S), Woodland (W), Forest (F)

Table XXVIII. Summary of San Pedro site characteristics, including floodplain width and patch types. Sites are listed from upstream to downstream.

SAN PEDRO RIVER *(Non-effluent control)*					
Site Name	Floodplain zone (m)	Transect	Patch types	No. of patches	No. of woody plots
Lewis Springs	187	1	H S F	6	9
	128	2	H S F	5	7
Fairbanks	72	1	H W	4	4
	65	2	H W	3	3
Narrows	80	1	H S W	3	12*
	274	2	H S W	8	
Three Links Farm #1	231	1	O H S W F	11	10*
	188	2	H S W F	9	
Three Links Farm #3	180	1	H S W F	11	13*
	167	2	H S W F	8	
Spirit Hollow Intermittent	312	1	O H S W	12	15*
	430	2	O H S W	15	
Spirit Hollow Perennial	382	1	O H S W F	13	18*
	410	2	O H S W F	14	
H&E #3	372	1	H S W	10	24*
	397	2	H S W F	19	
TNC Preserve P	602	1	H S W F	15	26*
	503	2	H S W F	14	

Patch types = Open (O), Herbaceous (H), Shrubland (S), Woodland (W), Forest (F)
**woody data plots were only established along 1 transect on wider floodplains*

Table XXIX. Frequency of occurrence for species recorded along Upper and Lower Santa Cruz transects. P indicates a species was not recorded within a study plot, but was present along the 20 m wide belt transect.

		upstream of NIWWTP (n = 47)		Upper Santa Cruz (n = 62)		Lower Santa Cruz (n = 68)	
Scientific name	Common name	#	%	#	%	#	%
Hydric Pioneer							
Baccharis salicifolia	Seep Willow	0	0	12	19	14	21
Populus fremontii	Fremont Cottonwood	6	13	14	23	2	3
Salix exigua	Coyote Willow	1	2	P		P	
Salix gooddingii	Gooding Willow	1	2	7	11	19	28
Mesic Non-Pioneer							
Celtis reticulata	Netleaf Hackberry	8	17	3	5	0	0
Fraxinus velutina	Velvet Ash	0	0	2	3	0	0
Juglans major	Arizona Walnut	0	0	2	3	0	0
Sambucus nigra	Black Elderberry	P	0	8	13	0	0
Xeromesic Pioneer							
Baccharis sarothroides	Desert Broom	P	0	3	5	3	4
Chilopsis linearis	Desert Willow	0	0	1	2	0	0
Hymenoclea monogyra	Single whorl Burrobrush	5	12	16	26	8	12
Salix taxifolia	Yewleaf Willow	0	0	2	3	0	0
Tamarix ramosissima	Salt Cedar	P	0	10	16	25	37
Xeromesic Non-Pioneer							
Parkinsonia sp.	Paloverde	P	0	P	0	15	22
Prosopis velutina	Velvet Mesquite	6	13	14	23	26	38
Xeric Secondary Successional							
Acacia greggii	Catclaw Acacia	P	0	1	2	P	0
Larrea tridentata	Creosote Bush	0	0	P	0	P	0
Lycium sp.	Wolfberry	1	2	0	0	0	0

Table XXX. Frequency of occurrence for species recorded along transects in the upper and lower San Pedro River basins. P indicates a species was not recorded within a study plot, but was present along the 20 m wide belt transect.

		Upper Basin (5 sites, n = 58)		Lower Basin (4 sites, n = 83)	
Scientific name	Common name	#	%	#	%
Hydric Pioneer					
Baccharis salicifolia	Seep Willow	18	31	21	25
Populus fremontii	Fremont Cottonwood	14	24	18	22
Salix exigua	Coyote Willow	5	9	3	4
Salix gooddingii	Gooding Willow	11	19	11	13
Mesic Non-Pioneer					
Celtis reticulata	Netleaf Hackberry	5	9	P	
Fraxinus velutina	Velvet Ash	4	5	0	0
Juglans major	Arizona Walnut	2	3	1	<1
Xeromesic Pioneer					
Baccharis sarothroides	Desert Broom	1	2	7	8
Chilopsis linearis	Desert Willow	P		P	
Hymenoclea monogyra	Single whorl Burrobrush	3	5	16	19
Hymenoclea salsola	Burrobrush	1	2	0	0
Tamarix ramosissima	Salt Cedar	21	36	50	60
Xeromesic Non-Pioneer					
Parkinsonia sp.	Paloverde	0	0	2	2
Prosopis velutina	Velvet Mesquite	23	40	20	23
Xeric Non-Pioneer					
Acacia greggii	Catclaw Acacia	2	3	1	<1
Atriplex canescens	Fourwing Saltbush	2	3	0	0
Larrea tridentata	Creosote Bush	P		1	<1
Lycium sp.	Wolfberry	2	3	2	2
Ziziphus obtusifolia	Lotebush	2	3	2	2

Table XXXI. Canopy cover, basal area, stem density and importance values by functional groups for the upper and lower Santa Cruz River. Canopy cover and stem density reported as weighted mean ± 1 standard deviation. Importance values are calculated as the average of relative stem density and relative basal area for each species.

Canopy Cover (%)

	Upper Santa Cruz							**Lower Santa Cruz**				
Functional Group	*-10*	*-5*	*15*	*25*	*35*	*45*	*55*	*8*	*15*	*30*	*45*	*60*
Hydric Pioneer	1	0	73	16	<1	0	0	5	3	24	16	11
Mesic Non-Pioneer	0	<1	0	0	0	0	0	0	0	0	0	0
Xeromesic Pioneer	0	0	0	4	7	0	0	3	2	3	0	0
Xeromesic Non-Pioneer	<1	3	31	1	<1	1	3	0	1	4	17	7
Xeric Non-Pioneer	0	0	0	0	0	<1	0	0	<1	0	0	0

Basal Area (m^2/ ha)

	Upper Santa Cruz							**Lower Santa Cruz**				
Functional Group	*-10*	*-5*	*15*	*25*	*35*	*45*	*55*	*8*	*15*	*30*	*45*	*60*
Hydric Pioneer	1	1	50	7	6	0	0	5	25	10	2	1
Mesic Non-Pioneer	0	3	5	0	0	0	0	0	0	0	0	0
Xeromesic Pioneer	0	0	0	3	2	0	1	<1	1	40	<1	0
Xeromesic Non-Pioneer	<1	3	16	0	1	0	1	0	1	<1	1	3
Xeric Non-Pioneer	<1	1	0	<1	1	<1	<1	<1	<1	<1	0	1

Stem Density (# stems/ha)

	Upper Santa Cruz							**Lower Santa Cruz**				
Functional Group	*-10*	*-5*	*15*	*25*	*35*	*45*	*55*	*8*	*15*	*30*	*45*	*60*
Hydric Pioneer	1	1	62	9	1	0	0	35	36	12	11	14
Mesic Non-Pioneer	0	3	33	0	0	0	0	0	0	0	0	0
Xeromesic Pioneer	0	0	0	22	26	0	0	23	15	48	<1	0
Xeromesic Non-Pioneer	1	3	13	0	5	0	2	<1	3	1	28	33
Xeric Non-Pioneer	1	3	0	3	150	12	10	<1	12	9	0	2

Importance Value (%)

	Upper Santa Cruz							**Lower Santa Cruz**				
Functional Group	*-10*	*-5*	*15*	*25*	*35*	*45*	*55*	*8*	*15*	*30*	*45*	*60*
Hydric Pioneer	61	23	66	56	23	0	0	73	64	46	49	39
Mesic Non-Pioneer	0	24	12	0	0	0	0	0	0	0	0	0
Xeromesic Pioneer	0	33	0	39	42	0	14	27	20	44	24	0
Xeromesic Non-Pioneer	25	17	21	1	5	29	54	0	8	5	21	60
Xeric Pioneer	14	2	0	3	30	71	31	0	8	4	6	1

Table XXXII. Canopy cover, basal area, stem density, and importance values by functional groups for the San Pedro River. Canopy cover and stem density reported as weighted mean ± 1 standard deviation. Importance values are calculated as the average of relative stem density and relative basal area for each species.

Canopy Cover (%)

	Perennial			Intermittent					
Functional Group	*LS*	*3L1*	*TNC*	*SHP**	*FB*	*3L3*	*SHI*	*NAR*	*HE3*
Hydric Pioneer	20	35	68	22	49	12	11	0	0
Mesic Non-Pioneer	0	0	0	0	0	0	0	0	0
Xeromesic Pioneer	0	48	6	10	0	29	32	18	45
Xeromesic Non-Pioneer	3	4	0	6	6	6	0	30	2
Xeric Non-Pioneer	0	0	0	0	0	0	0	0	0

Basal Area (m^2/ha)

	Perennial			Intermittent					
Functional Group	*LS*	*3L1*	*TNC*	*SHP**	*FB*	*3L3*	*SHI*	*NAR*	*HE3*
Hydric Pioneer	34	11	54	24	19	7	4	0	<1
Mesic Non-Pioneer	0	<1	0	0	<1	0	0	0	0
Xeromesic Pioneer	0	19	5	3	0	24	6	37	9
Xeromesic Non-Pioneer	1	1	1	1	10	4	<1	30	1
Xeric Non-Pioneer	0	0	<1	<1	<1	<1	<1	<1	<1

Stem Density (# stems/ha)

	Perennial			Intermittent					
Functional Group	*LS*	*3L1*	*TNC*	*SHP**	*FB*	*3L3*	*SHI*	*NAR*	*HE3*
Hydric Pioneer	68	13	27	113	12	47	112	0	6
Mesic Non-Pioneer	0	0	0	0	6	0	0	0	0
Xeromesic Pioneer	0	38	20	97	0	24	530	13	134
Xeromesic Non-Pioneer	21	4	2	50	25	4	3	29	23
Xeric Non-Pioneer	14	3	12	16	1	3	15	1	8

Importance Value (%)

	Perennial			Intermittent					
Functional Group	*LS*	*3L1*	*TNC*	*SHP**	*FB*	*3L3*	*SHI*	*NAR*	*HE3*
Hydric Pioneer	86	19	76	61	33	32	26	0	1
Mesic Non-Pioneer	0	0	0	0	3	0	0	0	0
Xeromesic Pioneer	0	44	16	24	0	58	72	41	89
Xeromesic Non-Pioneer	7	23	6	12	30	8	1	59	7
Xeric Non-Pioneer	6	13	2	3	34	1	1	1	2

Table XXXIII. Site-level canopy cover, basal area, and stem density for the upper and lower Santa Cruz reaches

	distance (km)	Canopy Cover (%)	Basal Area (m^2/ha)	Stem Density (# stems/ha)
Santa Fe Ranch	*-10*	2	2	4
Calabasas	*-5*	3	7	10
Santa Gertudis	*15*	89	70	108
Chavez Siding	*25*	22	24	35
Amado	*35*	8	9	96
Continental	*45*	2	< 1	12
Sahuarita	*55*	3	3	14
Ina	*8*	8	6	58
Avra Valley	*15*	6	27	65
Hardin	*30*	30	25	71
Sasco	*45*	33	3	22
Wheeler	*60*	18	5	48

Table XXXIV. Site-level canopy cover, basal area, and stem density for sites along the San Pedro River.

	flow permanence	Canopy Cover (%)	Basal Area (m^2/ha)	Stem Density (# stems/ha)
Lewis Springs	*Perennial*	30	35	109
Fairbank	*Intermittent*	22	29	44
Narrows	*Ephemeral*	28	68	42
Three Links 1	*Perennial*	80	30	59
Three Links 3	*Intermittent*	71	35	77
Spirit Hollow Int	*Intermittent*	38	10	660
Spirit Hollow Per	*Intermittent**	42	28	235
HE3	*Ephemeral*	46	9	171
TNC Per	*Perennial*	74	60	60

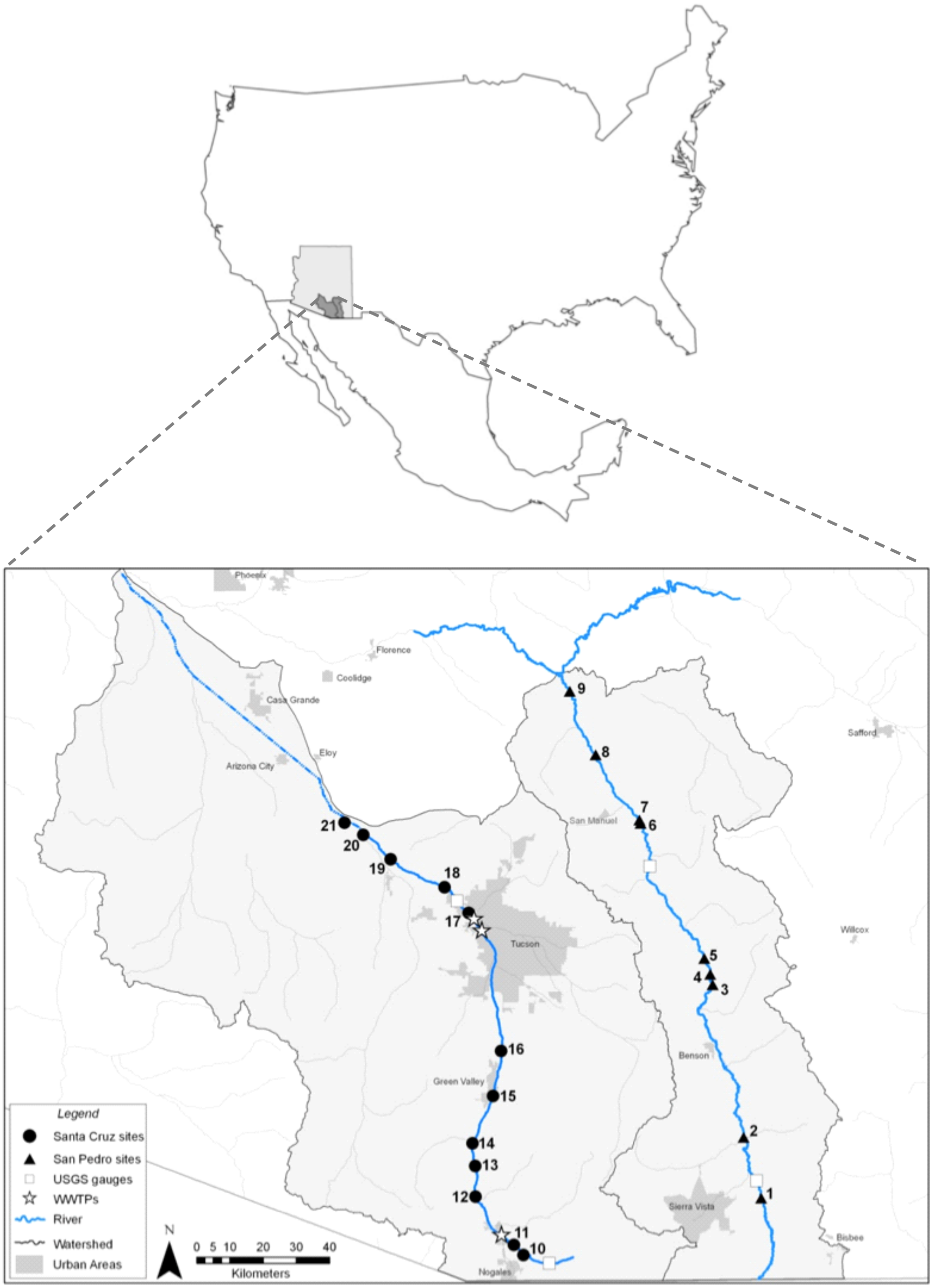


Figure 38. Map of effluent-dominated study river (Santa Cruz) and control river (San Pedro) showing locations of study sites, wastewater treatment facilities (WWTPs) and USGS stream gages. Site information is listed in Table XX.

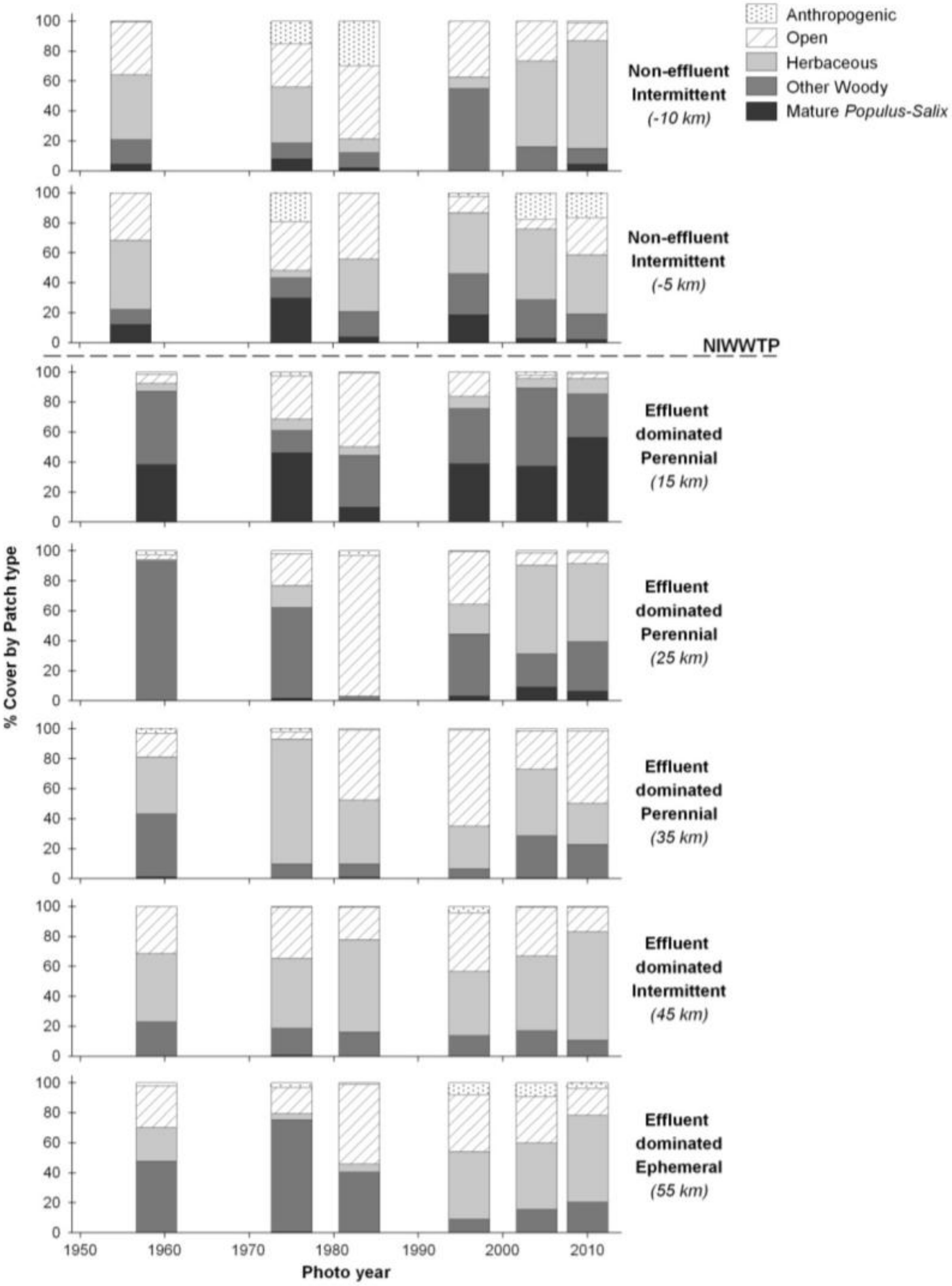


Figure 39. Changes in patch types from the 1950s to 2010 shown as a percentage of the floodplain in the effluent-dominated upper Santa Cruz River. Each graph represents a 1-km site.

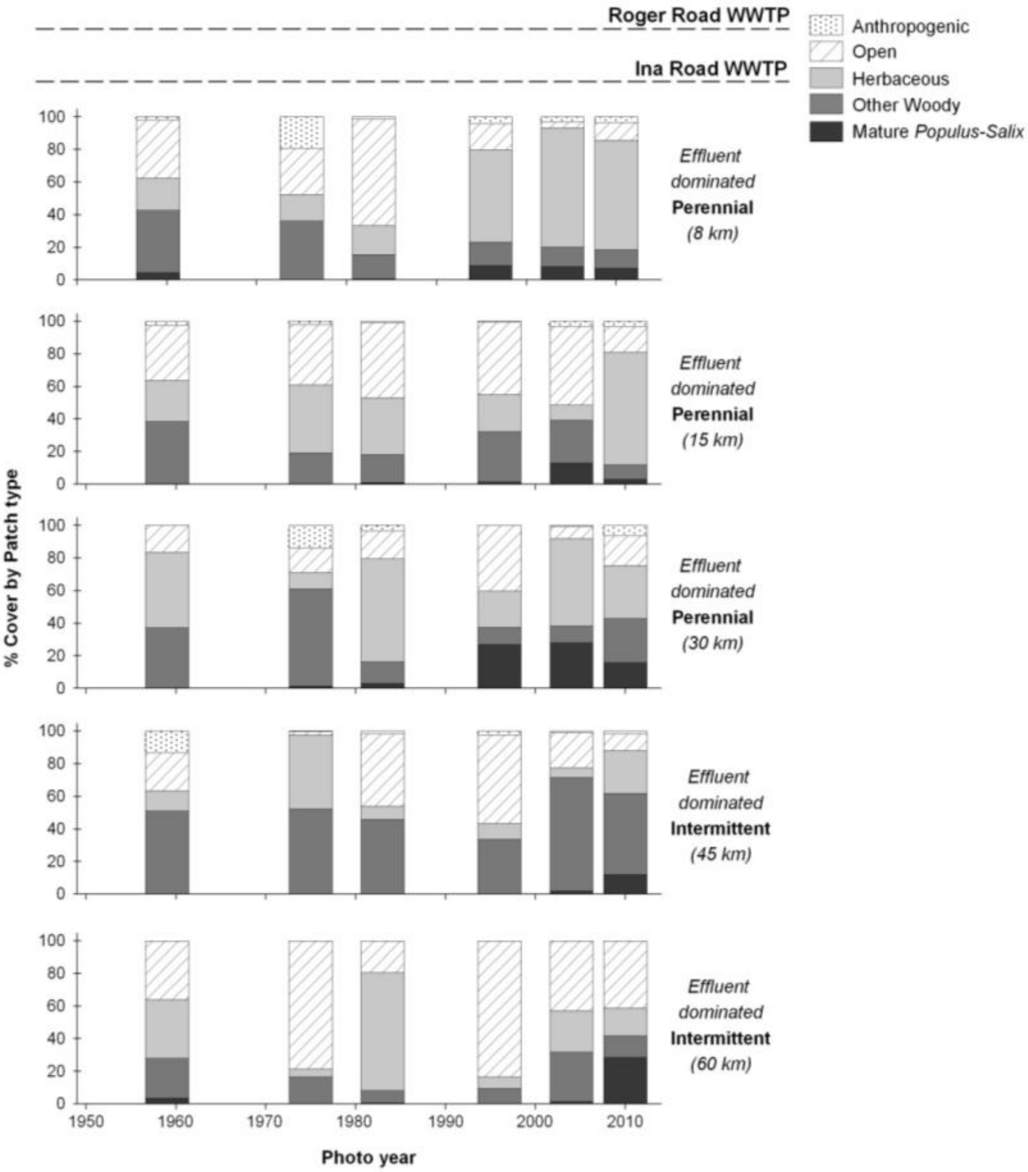


Figure 40. Historic patch changes shown as a percentage of the floodplain in the effluent-dominated lower Santa Cruz River. Each graph represents a 1-km site

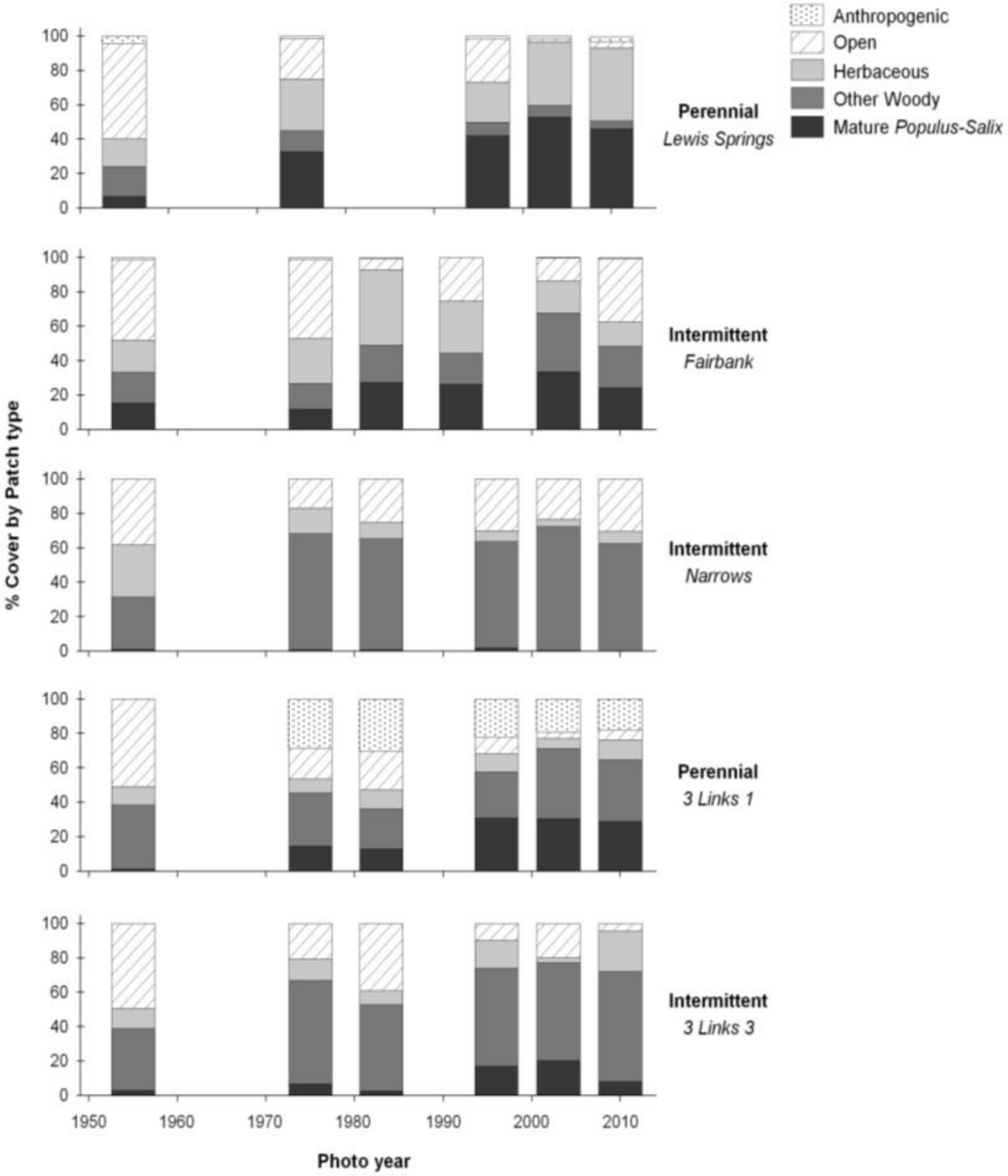


Figure 41. Historic patch changes shown as a percentage of the floodplain in the upper basin of the San Pedro River. Each graph represents a 1-km site.

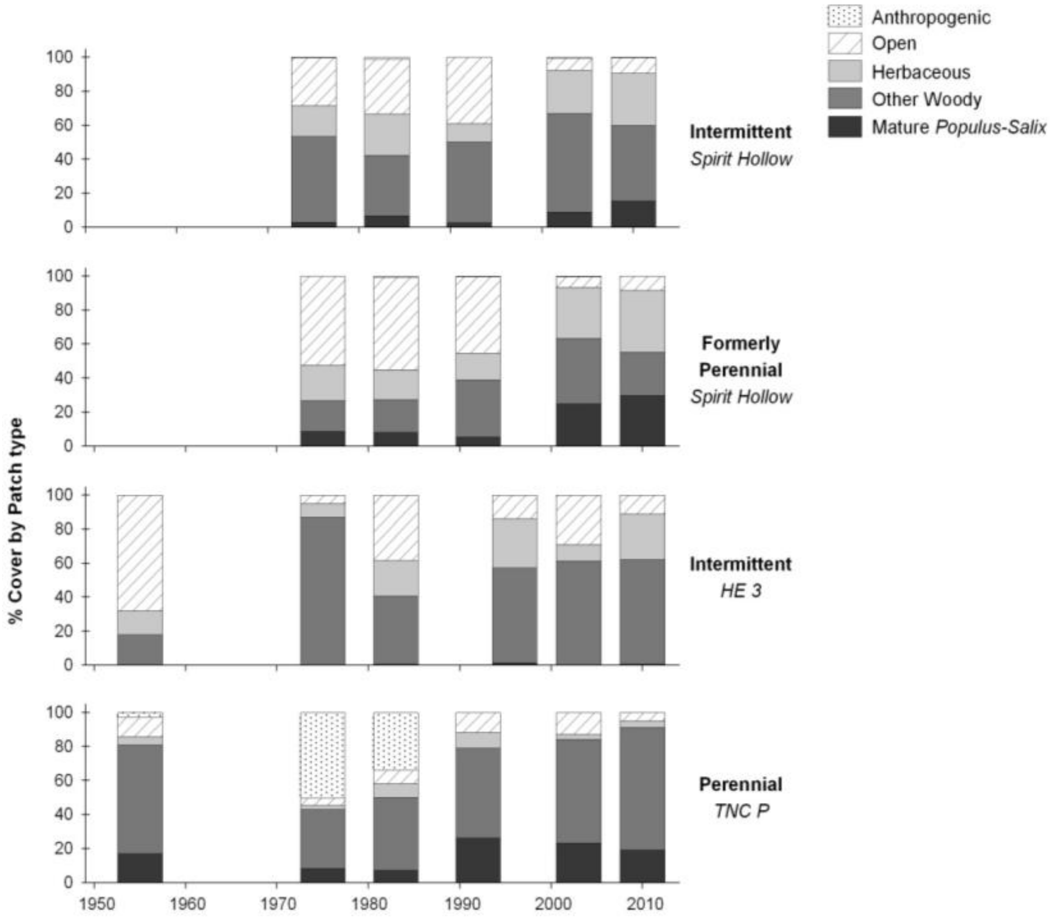


Figure 42. Historic patch changes shown as a percentage of the floodplain in the lower basin of the San Pedro River. Each graph represents a 1-km site

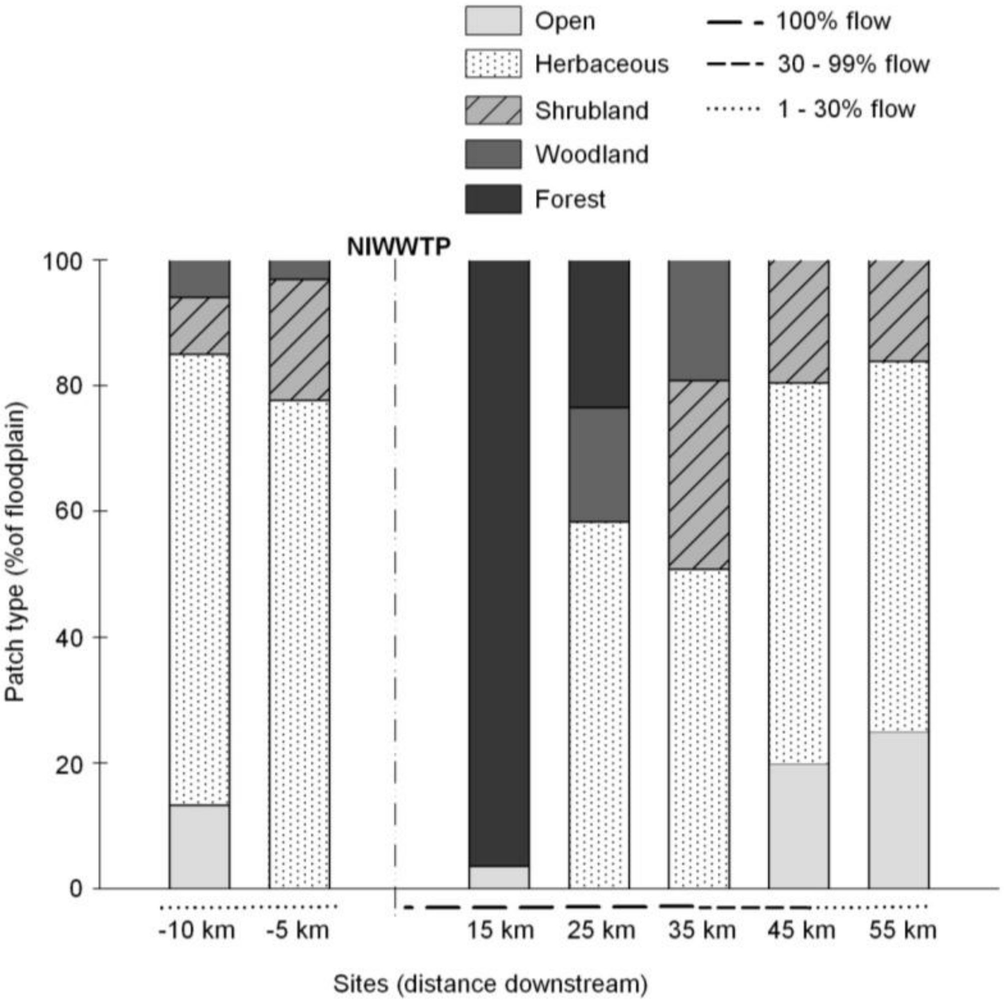


Figure 43. Relative areas occupied by different vegetation patch types in the upper Santa Cruz River. Surface flow permanence and distance from NIWWTP outfall are indicated along the x-axis

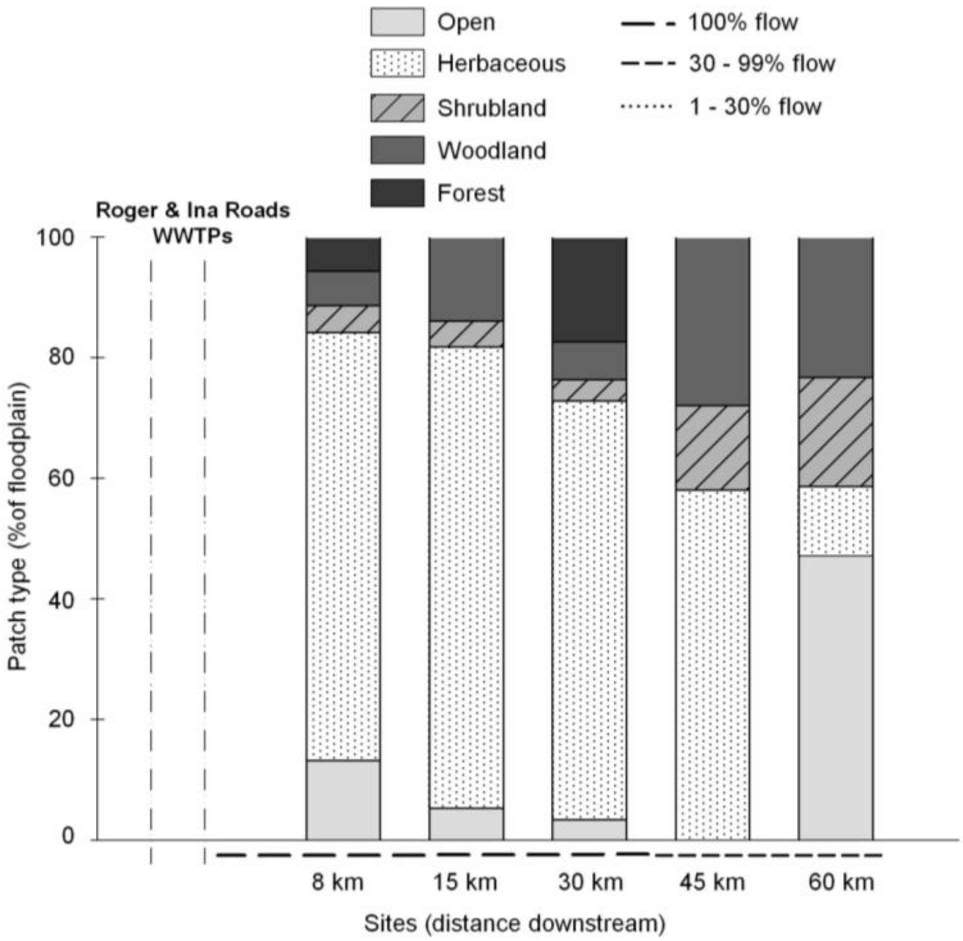


Figure 44. Relative areas occupied by different vegetation patch types in the lower Santa Cruz River. Surface flow permanence and distance from Roger and Ina WWTPs are indicated along the x-axis

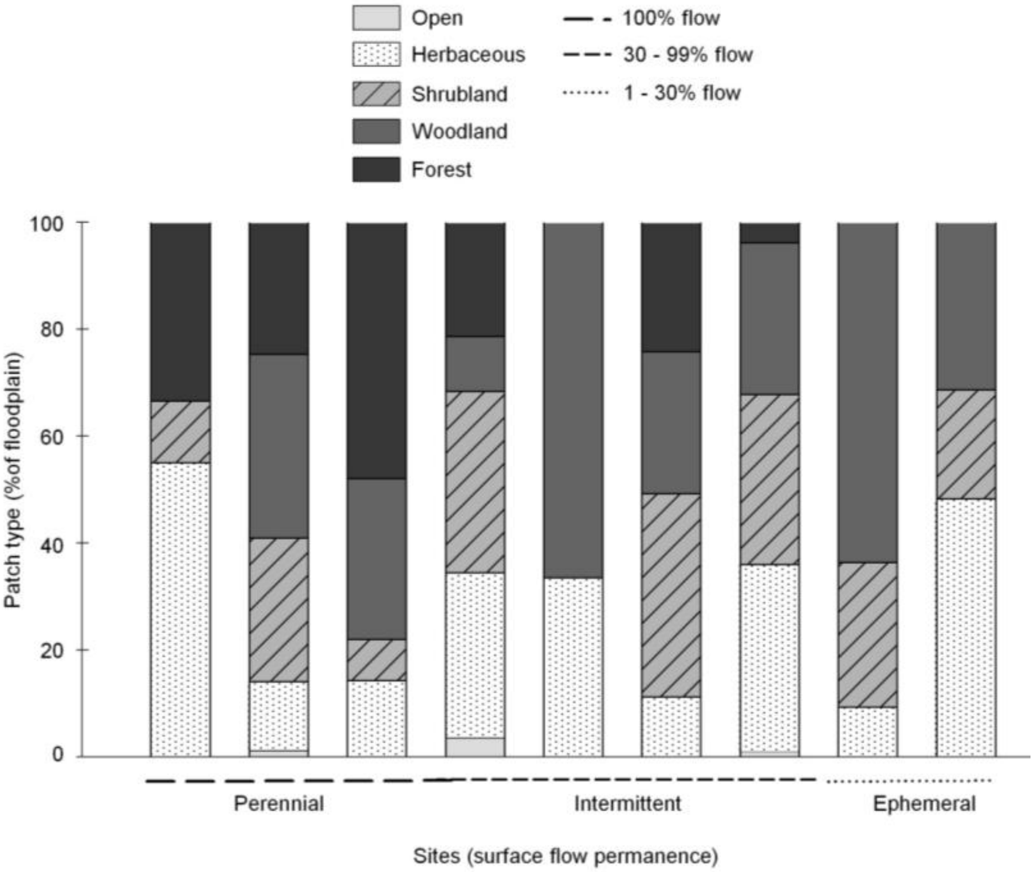


Figure 45. Relative areas occupied by different vegetation patch types along the San Pedro River. Surface flow permanence is indicated along the x-axis.

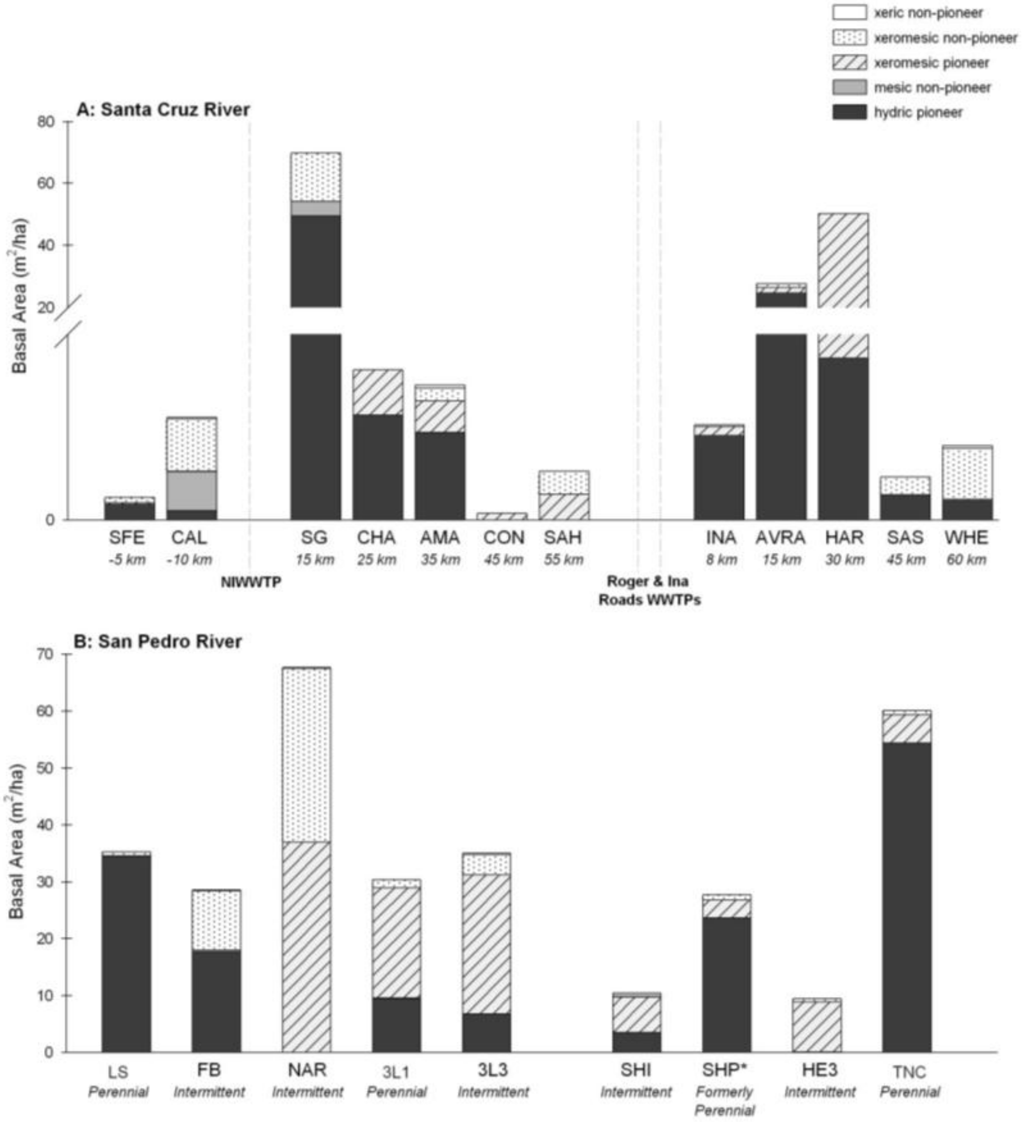


Figure 46. Basal area by moisture requirement of species along the (A) effluent-dominated Santa Cruz River and (B) the non-effluent San Pedro River. Sites with perennial flow tended to have greater basal area and a large percentage of that basal area was hydric species.

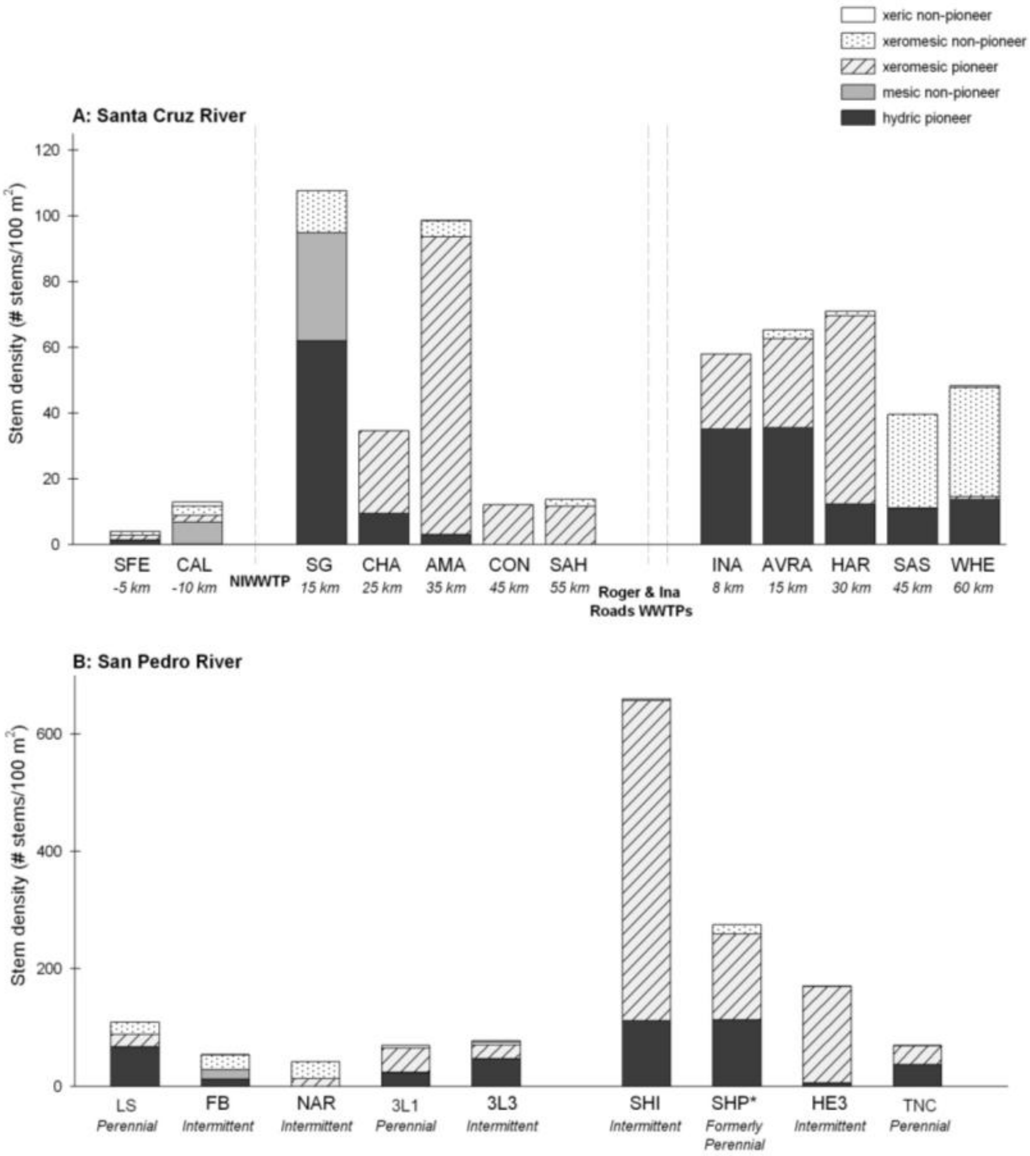


Figure 47. Stem density by moisture requirement of species along the (A) effluent-dominated Santa Cruz River and (B) the non-effluent San Pedro River

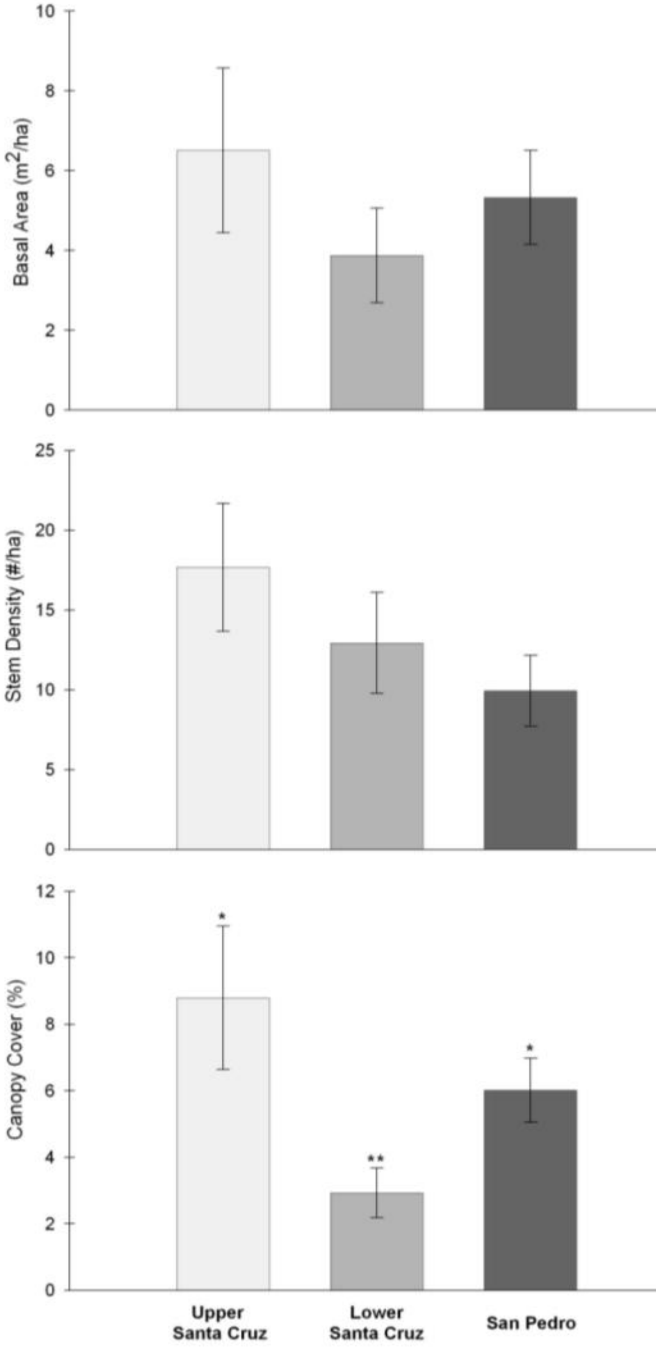


Figure 48. Kruskal-Wallis comparisons of woody plant community metrics at perennial sites in the effluent-dominated upper Santa Cruz, effluent-dominated lower Santa Cruz, and non-effluent San Pedro Rivers. Significant differences are highlighted with an asterisk (*). Error bars = +/- 1 SE

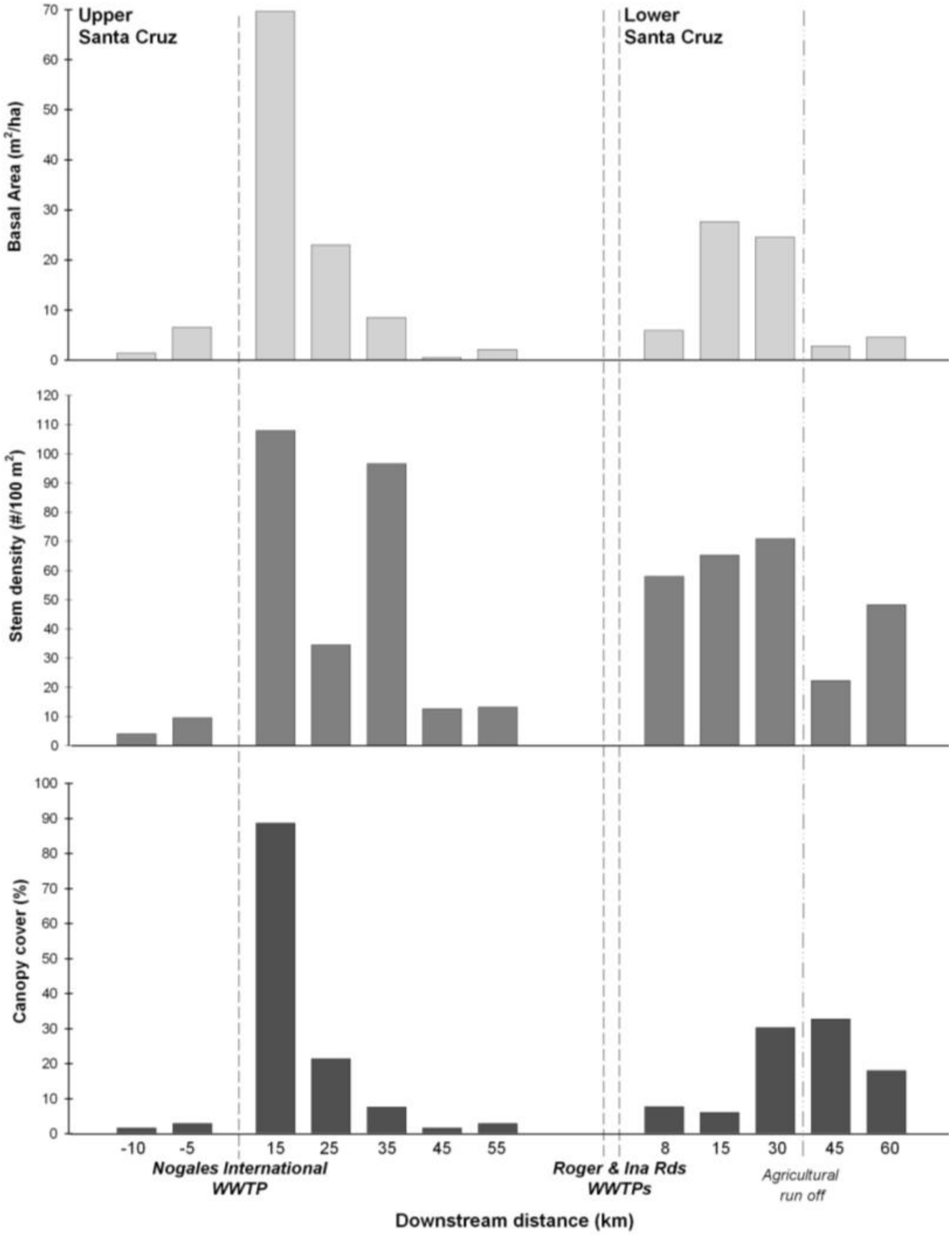


Figure 49. Relationship of basal area, stem density, and canopy cover with increasing distance from point of effluent discharge for the upper and lower Santa Cruz River.

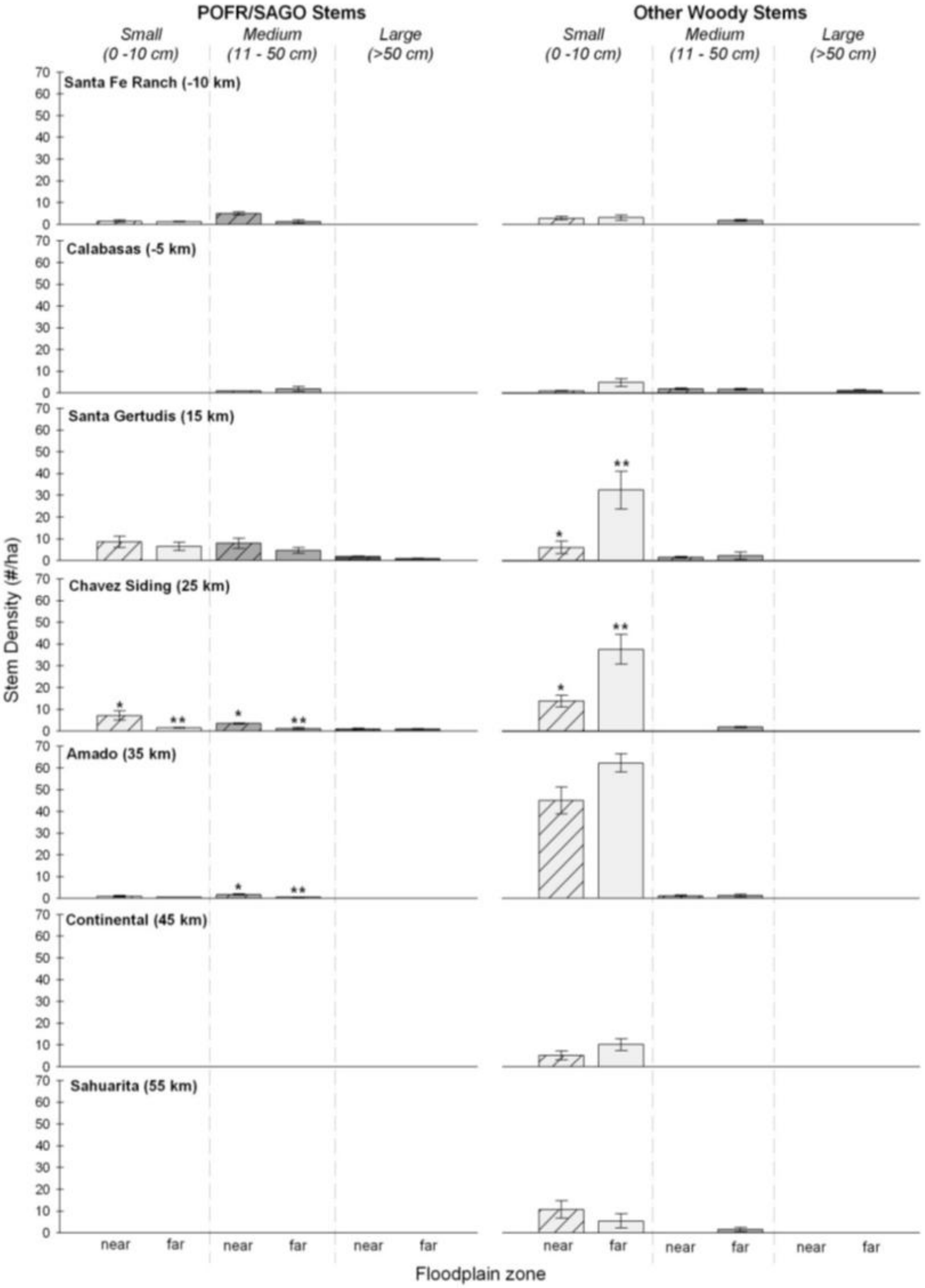


Figure 50. Kruskal-Wallis comparisons by size classes in the near and far floodplain zones of the effluent-dominated upper Santa Cruz. Significant differences are highlighted with an asterisk (*). Error bars = +/- 1 SE

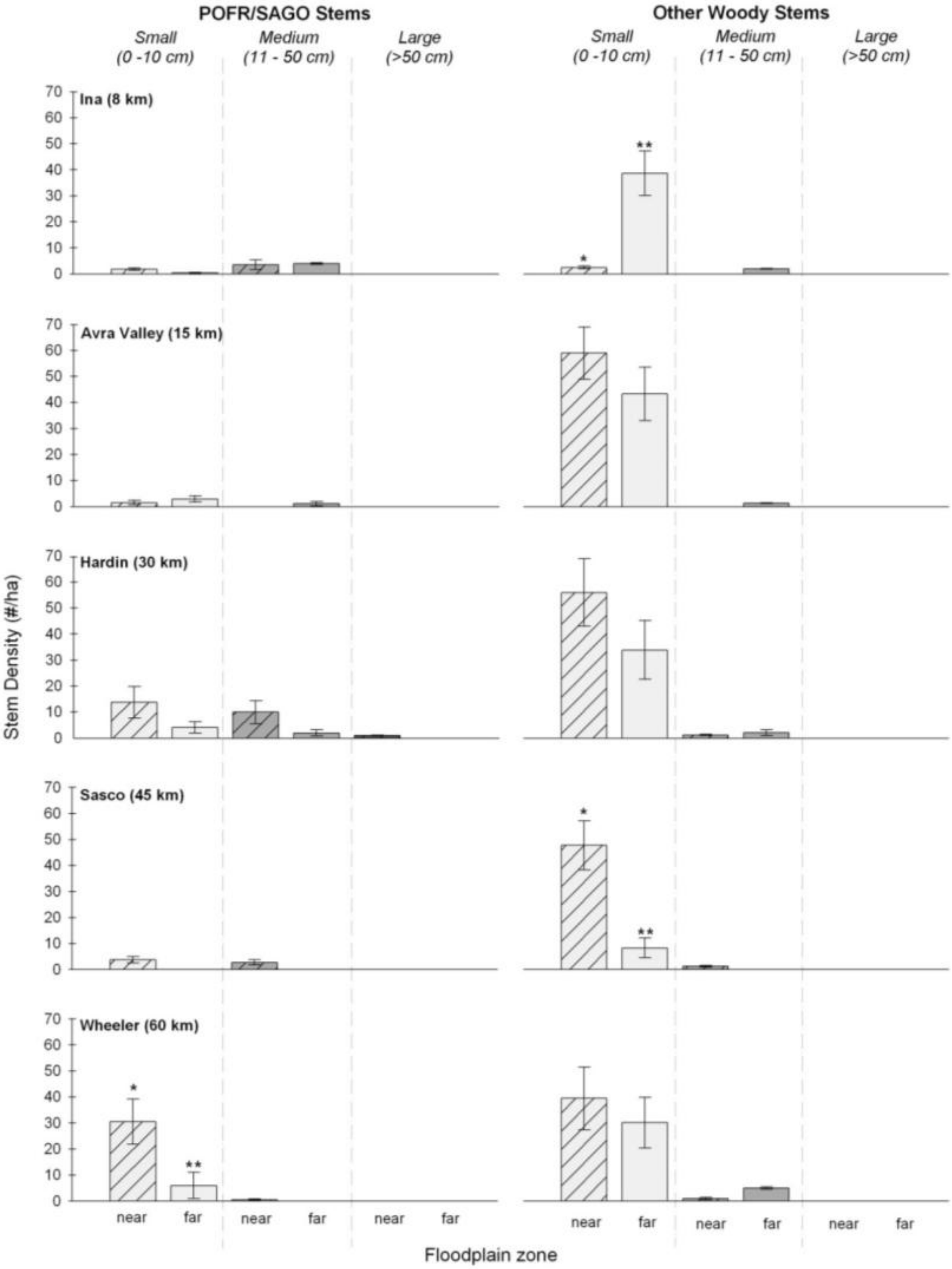


Figure 51. Kruskal-Wallis comparisons by size classes in the near and far floodplain zones of the effluent-dominated upper Santa Cruz. Significant differences are highlighted with an asterisk (*). Error bars = +/- 1 SE

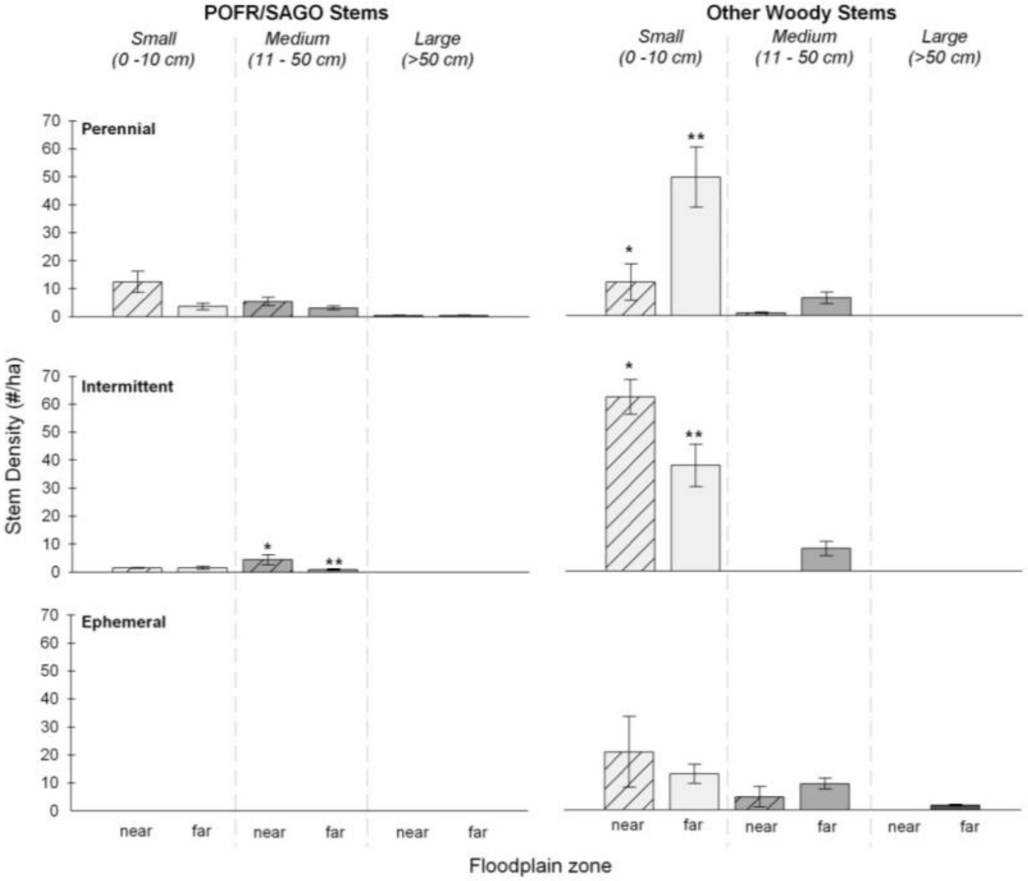


Figure 52. Kruskal-Wallis comparisons by size classes in the near and far floodplain zones ofthe non-effluent San Pedro River. Each graph represents one of three site types (perennial [3 Links 1], intermittent [3 Links 3], and ephemeral [Narrows]) sampled (total sites = 9). Significant differences are highlighted with an asterisk (*). Error bars = +/- 1 SE

6. CONCLUSIONS

The management and maintenance of river systems in the southwestern United States is becoming increasingly complex due to human impacts, multiple and competing water needs, and policy barriers. The interrupted perennial Santa Cruz River in southern Arizona provided a valuable setting in which to study ecological dynamics of an effluent-dominated riparian ecosystem with varying underlying hydrologic conditions. A control river, the San Pedro, provided a important contrast. Analysis of the riparian plant communities in the upper and lower Santa Cruz River revealed an increase in riparian vegetation downstream of effluent discharge points. Both effluent reaches had distinct longitudinal trends, with composition shifting from hydric species nearest the effluent release points to more xeromesic species further downstream as streamflow intermittency increased. In the shallow-groundwater, upper Santa Cruz River, we found a clear trend of decreasing abundance with increasing distance from treatment facility. The trends in the deep-groundwater, lower Santa Cruz were confounded by increased agricultural input further downstream.

Effluent discharged into the upper Santa Cruz supports is sustaining a mixture of obligate riparian floodplain species that require a dependable and accessible water supply and facultative species that are able to survive greater water level fluctuation. The dominant phreatophytes of along this reach of the Santa Cruz are Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii),* elderberry *(Sambucus nigra)*, *mesquite (Prosopis velutina), and netleaf hackberry (Celtis laevigata var. reticulata),* and are similar in scope to those of the control river. In the deep-groundwater lower Santa Cruz reach, the effluent sustains a narrower strip of woody vegetation that included Goodding willow (*Salix gooddingii),* mesquite (*Prosopis velutina*), single-whorl cheesebush (*Hymenoclea monogyra*), and tamarisk (*Tamarix ramosissima*). There was very little Fremont cottonwood (*Populus fremontii*) supported in the deep-groundwater lower reach, for reasons that remain unknown.

Herbaceous vegetation patterns were most revealing of water quality and lateral water availability, with the majority of herbaceous cover occurring within the first two meters of the channel and decreasing with lateral distance from the channel. This sharp decline across the floodplain was especially pronounced in the deep-groundwater lower reach. Finally, high levels of nutrients increased biomass in the streamside plant communities of both reaches, and shifted plant community composition toward more nitrophilic, or high nitrogen, species.

This work contributes to baseline knowledge regarding riparian vegetation dynamics along effluent-dominated systems across multiple spatial and temporal scales. It also underscores the growing need for additional research to evaluate the ecological integrity and longevity of these systems. From a management perspective, some of the changes in vegetation composition (e.g., nitrophiles) highlight the complex relationships between external factors (i.e., water availability) and system-specific components (i.e., water quality). This research also has shown that the composition and amount of habitat are drastically different along effluent-dominated systems in varying hydrogeomorphic settings and these dynamics need to be considered in management frameworks.

Our analysis of existing water policy and law further illuminates the importance of integrating scientific information into decision frameworks to increase adaptive capacity and evaluate options for water reuse and supply management. Appropriate decision rules that incorporate scientific information are needed to inform future approaches to secure effluent for riparian ecosystem maintenance and restoration.

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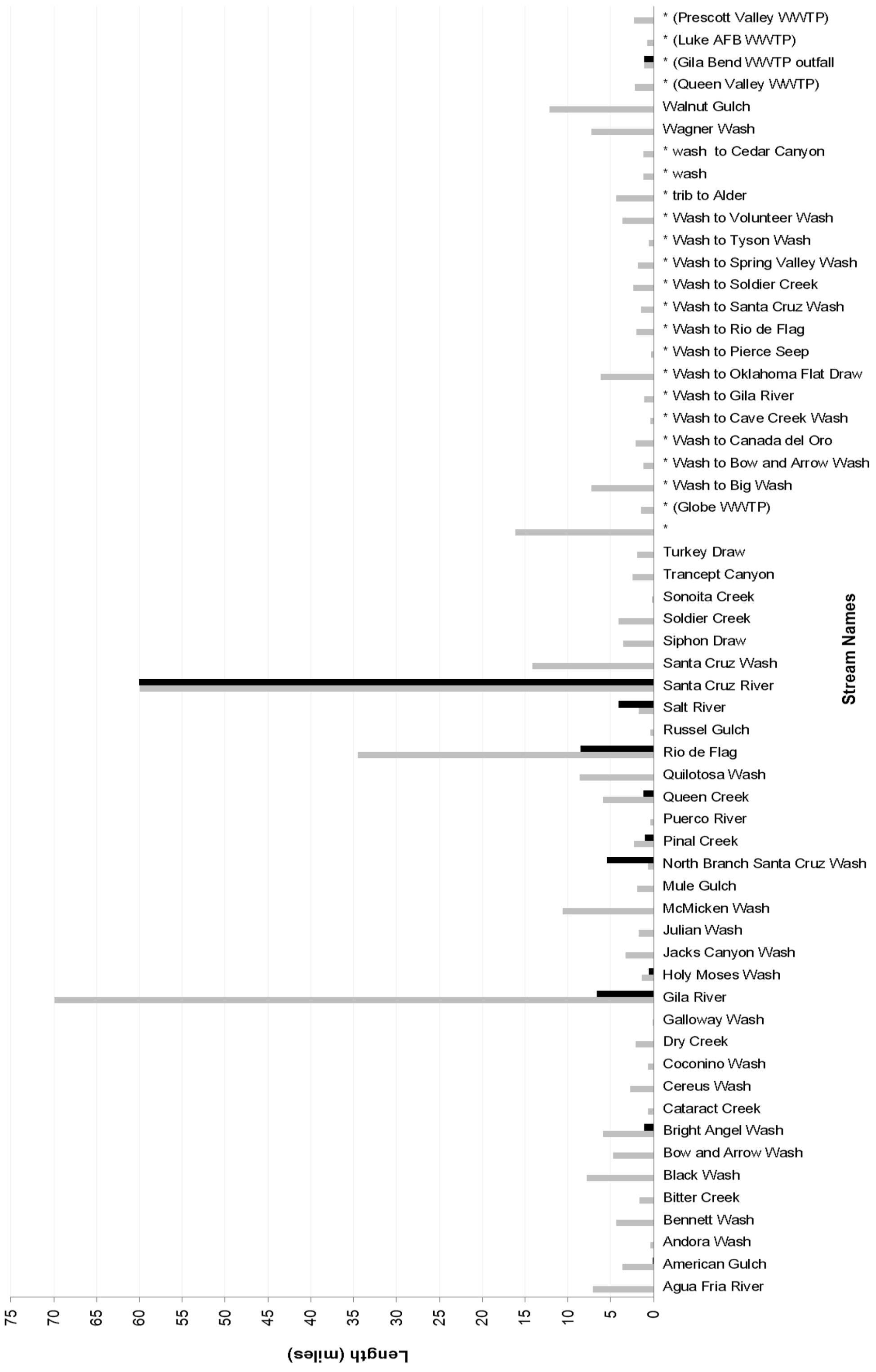
APPENDIX I

AWI VS AAC EFFLUENT DOMINATED FLOWS


* (Prescott Valley WWTP)
* (Luke AFB WWTP)
* (Gila Bend WWTP outfall
* (Queen Valley WWTP)
Walnut Gulch
Wagner Wash
* wash to Cedar Canyon
* wash
* trib to Alder
* Wash to Volunteer Wash
* Wash to Tyson Wash
* Wash to Spring Valley Wash
* Wash to Soldier Creek
* Wash to Santa Cruz Wash
* Wash to Rio de Flag
* Wash to Pierce Seep
* Wash to Oklahoma Flat Draw
* Wash to Gila River
* Wash to Cave Creek Wash
* Wash to Canada del Oro
* Wash to Bow and Arrow Wash
* Wash to Big Wash
* (Globe WWTP)
*
Turkey Draw
Trancept Canyon
Sonoita Creek
Soldier Creek
Siphon Draw
Santa Cruz Wash
Santa Cruz River
Salt River
Russel Gulch
Rio de Flag
Quilotosa Wash
Queen Creek
Puerco River
Pinal Creek
North Branch Santa Cruz Wash
Mule Gulch
McMicken Wash
Julian Wash
Jacks Canyon Wash
Holy Moses Wash
Gila River
Galloway Wash
Dry Creek
Coconino Wash
Cereus Wash
Cataract Creek
Bright Angel Wash
Bow and Arrow Wash
Black Wash
Bitter Creek
Bennett Wash
Andora Wash
American Gulch
Agua Fria River
Stream Names
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Length (miles)

APPENDIX II

EXPERIMENT SPECIES

Family	Genus species	Common name	WIS	Growth habit	Native/ Non-Native	Ephemeral	Effluent dominated	Perennial
Amaranthaceae	*Amaranthus palmeri*	carelessweed	4	F	N		√	√
Apiaceae	*Conium maculatum*	poison hemlock	1	F	NN		√	
Apiaceae	*Hydrocotyle verticillata*	whorled marsh pennywort	1	F	N		√	√
Apiaceae	*Bowlesia incana*	hoary bowlesia	5	F	N	√	√	
Asteraceae	*Baccharis salicifolia*	mule-fat	2	S	N	√	√	
Asteraceae	*Conyza canadensis*	Canadian horseweed	4	F	N		√	√
Asteraceae	*Pectis filipes*	fivebract chinchweed	5	F	N	√		
Asteraceae	*Pseudognaphalium canescens*	Wright's cudweed	5	F	N	√	√	√
Asteraceae	*Xanthium strumarium*	rough cocklebur	5	F	N	√		
Boraginaceae	*Amsinckia menziesii var. intermedia*	Common fiddleneck	5	F	N	√	√	
Brassicaceae	*Nasturtium officinale*	watercress	1	F	NN	√	√	√
Brassicaceae	*Sisymbrium irio*	London rocket	5	F	NN	√	√	√
Brassicaceae	*Dimorphocarpa wislizeni*	touristplant	5	F	N	√	√	
Convolvulaceae	*Ipomoea costellata*	crestrib morning-glory	4	V/F	N		√	
Cyperaceae	*Cyperus odoratus*	fragrant flatsedge	2	G	N		√	√
Euphorbiaceae	*Chamaesyce prostrata*	prostrate sandmat	5	F	N	√		
Fabaceae	*Prosopis velutina*	velvet mesquite	5	T	N	√		
Geraniaceae	*Erodium cicutarium*	redstem stork's bill	5	F	NN	√		
Juncaceae	*Juncus torreyi*	Torrey's rush	2	G	N	√		
Lamiaceae	*Hedeoma nana*	dwarf false pennyroyal	5	F	N		√	
Malvaceae	*Sphaeralcea coulteri*	Coulter's globemallow	5	SS/F	N	√		

Family	Genus species	Common name	WIS	Growth habit	Native/ Non-Native	Ephemeral	Effluent dominated	Perennial
Malvaceae	*Sphaeralcea laxa*	caliche globemallow	5	SS/F	N			√
Onagraceae	*Oenothera primiveris*	desert evening primrose	5	F	N	√	√	√
Nyctaginaceae	*Boerhavia coulteri*	Coulter's spiderling	5	F	N		√	
Poaceae	*Chloris virgata*	feather fingergrass	5	G	N	√		
Poaceae	*Cynodon dactylon*	Bermuda grass	4	G	NN		√	√
Poaceae	*Echinochloa colona*	jungle rice	2	G	NN	√	√	√
Poaceae	*Echinochloa crus-galli*	barnyardgrass	2	G	NN	√	√	√
Poaceae	*Eragrostis cilianensis*	stinkgrass	4	G	NN		√	√
Poaceae	*Eragrostis lehmanniana*	Lehmann lovegrass	4	G	NN		√	√
Poaceae	*Eragrostis pectinacea*	tufted lovegrass	3	G	N		√	√
Poaceae	*Eriochloa acuminata*	tapertip cupgrass	2	G	N	√	√	√
Poaceae	*Leptochloa panicea*	mucronate sprangletop	1	G	N		√	
Poaceae	*Polypogon monspeliensis*	annual rabbitsfoot grass	2	G	NN	√	√	√
Poaceae	*Schismus arabicus*	Arabian schismus	5	G	NN	√	√	√
Poaceae	*Setaria adhaerens*	bur bristlegrass	4	G	NN	√	√	√
Poaceae	*Setaria leucopila*	streambed bristlegrass	5	G	N	√	√	
Poaceae	*Sporobolus cryptandrus*	sand dropseed	4	G	N		√	
Polygonaceae	*Polygonum lapathifolium*	curlytop knotweed	1	F	N		√	
Polygonaceae	*Rumex crispus*	curly dock	2	F	NN		√	
Polygonaceae	*Rumex hymenosepalus*	canaigre dock	4	F	N	√		

Family	Genus species	Common name	WIS	Growth habit	Native/ Non-Native	Ephemeral	Effluent dominated	Perennial
Polygonaceae	*Portulaca oleracea*	little hogweed	3	F	N	√	√	
Ranunculaceae	*Ranunculus sceleratus*	cursed buttercup	1	F	N	√		√
Scrophulariaceae	*Mimulus guttatus*	seep monkeyflower	1	F	N	√	√	√
Scrophulariaceae	*Veronica anagallis-aquatica*	water speedwell	1	F	N	√	√	√
Solanaceae	*Calibrachoa parviflora*	seaside petunia	2	F	N	√		
Solanaceae	*Nicotiana glauca*	tree tobacco	3	T/S	NN	√	√	
Solanaceae	*Nicotiana obtusifolia var. obtusifolia*	desert tobacco	4	F/SS	N	√	√	
Verbenaceae	*Glandularia bipinnatifida*	Dakota mock vervain	4	F	N	√		
Zygophyllaceae	*Larrea tridentata*	creosote bush	5	S	N	√		

APPENDIX III

SANTA CRUZ SPECIES

Genus species	***Family***	***ABBR***	**Duration**	**Form**	**Wetland**	***WIS***	**N score**
Acalypha neomexicana	Euphorbiaceae	ACNE	A	F	N/A	5	
Acalypha ostryifolia	Euphorbiaceae	ACOS	A	F	N/A	5	
Amaranthus fimbriatus	Amaranthaceae	AMFI	A	F	N/A	4	7
Amaranthus palmeri	Amaranthaceae	AMPA	A	F	FACU	4	7
Ambrosia ambrosioides	Asteraceae	AMAM	P	S/SS	N/A	4	6
Ambrosia artemisiifolia	Asteraceae	AMAR	A	F	FACU	4	6
Ambrosia deltoidea	Asteraceae	AM_DE	P	S/SS	N/A	4	6
Ambrosia psilostachya	Asteraceae	AMPS	A/P	F	FAC	3	4
Ambrosia trifida	Asteraceae	AMTR	A	SS/F	FACW-	2	5
Androsace occidentalis	Primulaceae	ANOC2	A	F	FACU	4	2
Anoda cristata	Malvaceae	ANCR2	A	F	FAC	3	
Apodanthera undulata	Cucurbitaceae	APUN	P	V/F	NI	5	
Argemone pleiacantha subsp. Ambigua	Papaveraceae	ARPL3	P	F	NI	5	
Aristida adscensionis	Poaceae	ARAD	A	G	N/A	5	
Arundo donax	Poaceae	ARDO	P	SS/S/G	FACW	2	7
Astragalus thurberi	Fabaceae	ASTH	A/P	F	N/A	5	2
Baccharis salicifolia	Asteraceae	BASA	P	S	FACW	2	6
Baccharis sarothroides	Asteraceae	BASA2	P	S	FAC-	3	6
Bidens leptocephala	Asteraceae	BILE	A	F	FAC	3	8
Boerhavia coccinea	Nyctaginaceae	BOCO	P	F	N/A	5	2
Boerhavia coulteri	Nyctaginaceae	BOCO2	A	F	N/A	5	2
Bouteloua aristidoides	Poaceae	BOAR	A	G	N/A	5	1
Bouteloua rothrockii	Poaceae	BORO	P	G	N/A	5	1
Bowlesia incana	Apiaceae	BOIN	A	F	UPL	5	2
Bromus catharticus	Poaceae	BRCA	A/P	G	N/A	5	4
Calibrachoa parviflora	Solanaceae	CAPA	A	F	FACW	2	1
Celtis laevigata var. reticulata	Ulmaceae	CELAR	P	T/S	FACU	4	
Cenchrus spinifex	Poaceae	CESP	A/P	G	NI	4	
Chamaecrista nictitans	Fabaceae	CHNI	A/P	SS/F	NO	4	
Chamaesyce capitellata	Euphorbiaceae	CHCA	P	F	N/A	5	2
Chamaesyce florida	Euphorbiaceae	CHFL	A	F	N/A	5	2
Chamaesyce hyssopifolia	Euphorbiaceae	CHHY	A/P	F	NI	3	2

Genus species	***Family***	***ABBR***	***Duration***	***Form***	***Wetland***	***WIS***	**N score**
Chamaesyce setiloba	Euphorbiaceae	CHSE	A	F	N/A	5	2
Chenopodium ambrosioides	Chenopodiaceae	CHAM	A/P	F/SS	FAC	3	7
Chenopodium berlandieri	Chenopodiaceae	CHBE	A	F	N/A	4	7
Chenopodium fremontii	Chenopodiaceae	CHFR	A	F	UPL	5	7
Chloris virgata	Poaceae	CHVI	A	G	N/A	5	2
Cirsium vulgare	Asteraceae	CIVU	B	F	FACU	4	8
Clematis drummondii	Ranunculaceae	CLDR	P	V	N/A	4	5
Clematis hirsutissima	Ranunculaceae	CLHI	P	SS/F		4	5
Conium maculatum	Apiaceae	COMA	B	F	OBL	1	8
Conyza canadensis	Asteraceae	COCA	A/B	F	FACU	4	5
Crotalaria pumila	Fabaceae	CRPU	A/P	SS/F	N/A	5	
Croton pottsii	Euphorbiaceae	CRPO	P	SS/F	N/A	5	
Cryptantha angustifolia	Boraginaceae	CRAN	A	F	N/A	5	3
Cryptantha micrantha	Boraginaceae	CRMI	A	F	N/A	5	3
Cyclospermum leptophyllum	Apiaceae	CYLE	A	F	UPL	5	5
Cynodon dactylon	Poaceae	CYDA	P	G	FACU	4	5
Cyperus esculentus	Cyperaceae	CYES	P	G	FACW	2	5
Cyperus involucratus	Cyperaceae	CYIN	P	G	NO	2	5
Cyperus odoratus	Cyperaceae	CYOD	A/P	G	FACW+	2	5
Cyperus strigosus	Cyperaceae	CYST	P	G	FACW	2	5
Dactyloctenium aegyptium	Poaceae	DAAE	A	G	N/A	5	
Datura wrightii	Solanaceae	DAWR	A/P	F/SS	N/A	5	8
Daucus carota	Apiaceae	DACA	B	F	N/A	3	4
Descurainia pinnata	Brassicaceae	DEPI	A/B/P	F	N/A	5	6
Dicliptera resupinata	Acanthaceae	DIRE	P	F	N/A	5	
Digitaria sanguinalis	Poaceae	DISA	A	G	FACU	4	5
Distichlis spicata	Poaceae	DISP	P	G	FACW	2	2
Dysphania ambrosioides	Chenopodiaceae	DYAM	A/P	F	FAC	3	
Echinochloa colona	Poaceae	ECCO	A	G	FACW	2	8
Echinochloa crus-galli	Poaceae	ECCR	A	G	FACW-	2	8
Eclipta prostrata	Asteraceae	ECPR	A/P	F	FAC	3	

Genus species	Family	ABBR	Duration	Form	Wetland	WIS	N score
Equisetum laevigatum	Equisetaceae	EQLA	P	G	FACW	2	4
Eragrostis cilianensis	Poaceae	ERCI	A	G	FACU+	4	3
Eragrostis lehmanniana	Poaceae	ERLE	P	G	N/A	5	3
Eragrostis pectinacea	Poaceae	ERPE	A/P	G	FAC	3	3
Erigeron divergens	Poaceae	ERDI	B	F	N/A	5	4
Eriochloa acuminata	Poaceae	ERAC	A	G	FACW	2	3
Eriochloa aristata	Poaceae	ERAR	A	G	FACW	2	3
Eriogonum polycladon	Polygonaceae	ERPO	A	F	N/A	5	
Erodium cicutarium	Geraniaceae	ERCI2	A/B	F	N/A	5	3
Eschscholzia californica ssp. Mexicana	Papaveraceae	ESCAM	A/P	F	N/A	5	2
Euphorbia heterophylla	Euphorbiaceae	EUHE	A/P	F	UPL	5	4
Euphorbia micromera	Euphorbiaceae	CHMI	A/P	F	N/A	5	4
Gaura mollis	Onagraceae	GAMO	A	F	NI	4	
Helianthus annuus	Asteraceae	HEAN	A	F	FAC-	3	8
Heliotropium curassavicum	Boraginaceae	HECU	A/P	SS/F	FACW	2	6
Heterotheca subaxillaris	Asteraceae	HESU	A	F	UPL	5	
Hydrocotyle verticillata	Apiaceae	HYVE	P	F	OBL	1	2
Hymenoclea monogyra	Asteraceae	HYMO	P	SS/S	N/A	5	3
Ipomoea barbatisepala	Convovulaceae	IPBA	A	V/F	N/A	4	
Ipomoea cristulata	Convovulaceae	IPCR	A	V/F	N/A	4	2
Ipomoea hederacea	Convovulaceae	IPHE	A	V/F	FACU*	4	2
Ipomoea purpurea	Convovulaceae	IPPU	A	V/F	UPL	5	2
Ipomoea ternifolia	Convovulaceae	IPTE	A	F	N/A	4	2
Isocoma tenuisecta	Asteraceae	ISTE	P	SS/F	N/A	5	
Kallstroemia parviflora	Zygophyllaceae	KAPA	A	F	N/A	5	
Lepidium thurberi	Brassicaceae	LETH	A/B	F	N/A	4	5
Ludwigia palustris	Onagraceae	LUPA	P	F	OBL	1	4
Lupinus concinnus	Fabaceae	LUCO	A	F	N/A	5	
Machaeranthera canescens	Asteraceae	MACA	A/B/P	F	UPL	5	
Malacothrix glabrata	Asteraceae	MAGL	A	F	N/A	5	

Genus species	***Family***	***ABBR***	***Duration***	***Form***	***Wetland***	***WIS***	**N score**
Malva parviflora	Malvaceae	MAPA	A/B/P	F	N/A	5	
Melilotus alba	Fabaceae	MEAL	A/B/P	F	FACU+	4	4
Melilotus indicus	Fabaceae	MEIN	A	F	FACU+	4	7
Melilotus officinalis	Fabaceae	MEOF	A/B/P	F	FACU+	4	3
Mentzelia multiflora	Loasaceae	MEMU	B/P	F	N/A	5	4
Mimulus guttatus	Scrophulariaceae	MIGU	A/P	F	OBL	1	6
Mirabilis longiflora	Nyctaginaceae	MILO	P	F	N/A	4	3
Nama hispidum	Hydrophyllaceae	NAHI	A	F	N/A	5	
Nasturtium officinale	Brassicaceae	NAOF	P	F	OBL	1	7
Nicotiana glauca	Solanaceae	NIGL	P	T/S	FAC	3	6
Nicotiana obtusifolia	Solanaceae	NIOB	A/B/P	F/SS	FACU	4	6
Panicum antidotale	Poaceae	PAAN	P	G	N/A	5	6
Parkinsonia sp.	Fabaceae	PASP	P	T	N/A		
Paspalum dilatatum	Poaceae	PADI	P	G	FAC	3	
Pectis papposa	Asteraceae	PEPA	A	F	N/A	5	
Pectis prostrata	Asteraceae	PEPR	A	F	N/A	5	
Phacelia arizonica	Solanaceae	PHAR	P	F	N/A	5	
Physalis acutifolia	Solanaceae	PHAC	A	F	N/A	5	7
Polygonum lapathifolium	Polygonaceae	POLA	A	F	OBL	1	8
Polypogon monspeliensis	Poaceae	POMO	A	G	FACW+	2	6
Populus fremontii	Salicaceae	POFR	P	T	FACW	2	6
Portulaca halimoides	Portulaceae	POHA	A	F	NO	4	7
Portulaca oleracea	Portulaceae	POOL	A	F	FAC	3	7
Portulaca suffrutescens	Portulaceae	POSU	P	SS/F	N/A	4	7
Proboscidea parviflora	Pedaliaceae	PRPA	A	F	N/A	5	
Prosopis velutina	Fabaceae	PRVE	P	T/S	N/A		
Pseudognaphalium canescens	Asteraceae	PSCA	A/B/P	F	UPL	5	2
Ranunculus sceleratus	Ranunculaceae	RASC	A/P	F	OBL	1	9
Rumex dentatus	Polygonaceae	RUDE	A/B	F	NO	1	6
Rumex obtusifolius	Polygonaceae	RUOB	P	F	FACW	2	9
Salix gooddingii	Salicaceae	SAGO	P	T	OBL	1	5

Genus species	***Family***	***ABBR***	***Duration***	***Form***	***Wetland***	***WIS***	**N score**
Salsola tragus	Chenopodiaceae	SATR	A	F	FACU	4	6
Schismus arabicus	Poaceae	SCAR	A	G	N/A	5	1
Schismus barbatus	Poaceae	SCBA	A	G	N/A	5	1
Schoenoplectus americanus	Cyperaceae	SCAM	P	G	OBL	1	7
Setaria grisebachii	Poaceae	SEGR	A	G	N/A	4	7
Sida spinosa	Malvaceae	SISP	A/P	SS/F	UPL	5	
Sisymbrium irio	Brassicaceae	SIIR	A	F	N/A	5	5
Solanum americanum	Solanaceae	SOAM	A/P	SS/F	FAC	3	7
Solanum elaeagnifolium	Solanaceae	SOEL	P	SS/F	N/A	5	7
Solanum lycopersicum	Solanaceae	SOLY	A/P	F	N/A	5	7
Sonchus asper	Asteraceae	SOAS	A	F	FACW	2	7
Sorghum halepense	Poaceae	SOHA	P	G	FACU+	4	4
Sphaeralcea laxa	Malvaceae	SPLA	P	F	NI	5	3
Sporobolus contractus	Poaceae	SPCO	P	G	N/A	4	4
Sporobolus cryptandrus	Poaceae	SPCR	P	G	FACU-	4	4
Stemodia durantifolia	Scrophulariaceae	STDU	A	F	OBL	1	
Symphyotrichum ascendens	Asteraceae	SYAS	P	F	N/A	5	
Tamarix ramosissima	Tamaricaceae	TARA	P	T/S	NI		
Tidestromia lanuginosa	Amaranthaceae	TILA	A	F	N/A	5	
Trianthema portulacastrum	Aizoaceae	TRPO	A/P	F	NI	2	
Typha domingensis	Typhaceae	TYDO	P	F	OBL	1	8
Urochloa arizonica	Poaceae	URAR	A	G	N/A	5	1
Verbesina encelioides	Asteraceae	VEEN	A	F	FAC	3	
Veronica anagallis-aquatica	Scrophulariaceae	VEAN	B/P	F	OBL	1	5
Vulpia octoflora	Poaceae	VUOC	A	G	NI	5	1
Xanthium strumarium	Asteraceae	XAST	A	F	NI	4	6

APPENDIX IV

SAN PEDRO SPECIES

Genus species	Family	abbr.	Duration	Form	Wetland	WIS	N score
Acalypha neomexicana	Euphorbiaceae	ACNE	A	F	N/A	5	
Acalypha ostryifolia	Euphorbiaceae	ACOS	A	F	N/A	5	
Amaranthus fimbriatus	Amaranthaceae	AMFI	A	F	N/A	4	7
Amaranthus palmeri	Amaranthaceae	AMPA	A	F	FACU	4	7
Ambrosia ambrosioides	Asteraceae	AMAM	P	S/SS	N/A	4	6
Ambrosia deltoidea	Asteraceae	AM_DE	P	S/SS	N/A	4	6
Ambrosia psilostachya	Asteraceae	AMPS	A/P	F	FAC	3	4
Ambrosia trifida	Asteraceae	AMTR	A	SS/F	FACW-	2	5
Amsinckia menziesii	Boraginaceae	AMME	A	F	N/A	5	
Anemopsis californica	Saururaceae	ANCA	P	F	OBL	1	
Astragalus nuttallianus	Asteraceae	ASNU	A/P	F	N/A	5	3
Avena fatua	Poaceae	AVFA	A	G	N/A	5	5
Baccharis emoryi	Asteraceae	BAEM	P	S	FACW	2	
Baccharis salicifolia	Asteraceae	BASA	P	S	FACW	2	
Bidens leptocephala	Asteraceae	BILE	A	F	FAC	3	8
Boerhavia coccinea	Nyctaginaceae	BOCO	P	F	N/A	5	
Boerhavia coulteri	Nyctaginaceae	BOCO2	A	F	N/A	5	
Bothriochloa laguroides	Poaceae	BOLA	P	G	N/A	5	3
Bouteloua aristidoides	Poaceae	BOAR	A	G	N/A	5	
Bouteloua barbata	Poaceae	BOBA	A	G	N/A	5	
Bowlesia incana	Apiaceae	BOIN	A	F	UPL	5	
Brickellia californica	Asteraceae	BRCA3	P	SS/S	FACU+	4	
Bromus catharticus	Poaceae	BRCA	A/P	G	N/A	5	4
Bromus diandrus	Poaceae	BRDI	A/P	G	N/A	5	4
Bromus rubens	Poaceae	BRRU	A	G	NI	5	4
Bromus tectorum	Poaceae	BRTE	A	G	N/A	5	4
Celtis laevigata var. reticulata	Ulmaceae	CELAR	P	T/S	FACU	4	
Cenchrus spinifex	Poaceae	CESP	A/P	G	NI	4	
Cephalanthus occidentalis	Rubiaceae	CEOC	P	T/S	OBL	1	
Chamaesyce capitellata	Euphorbiaceae	CHCA	P	F	N/A	5	
Chamaesyce hyssopifolia	Euphorbiaceae	CHHY	A/P	F	NI	3	

Genus species	**Family**	**abbr.**	**Duration**	**Form**	**Wetland**	**WIS**	**N score**
Chamaesyce micromera	Euphorbiaceae	CHMI	A	F	N/A	5	
Chamaesyce setiloba	Euphorbiaceae	CHSE	A	F	N/A	5	
Chenopodium album	Chenopodiaceae	CHAL	A	F	FACU	4	7
Chenopodium berlandieri	Chenopodiaceae	CHBE	A	F	N/A	4	7
Chenopodium botrys	Chenopodiaceae	CHBO	A	F	FACU	4	6
Chenopodium fremontii	Chenopodiaceae	CHFR	A	F	UPL	5	7
Chenopodium leptophyllum	Chenopodiaceae	CHLE	A	F	FACU	4	8
Chloracantha spinosa	Asteraceae	CHSP	P	SS/S/F	FACW	2	
Chloris virgata	Poaceae	CHVI	A	G	N/A	5	2
Cirsium vulgare	Asteraceae	CIVU	B	F	FACU	4	8
Clematis drummondii	Ranunculaceae	CLDR	P	V	N/A	4	5
Conyza canadensis	Asteraceae	COCA	A/B	F	FACU	4	5
Conyza coulteri	Asteraceae	LACO	A	F	FACW-	2	5
Cryptantha angustifolia	Boraginaceae	CRAN	A	F	N/A	5	3
Cryptantha muricata	Boraginaceae	CRMU	A	F	N/A	5	3
Cynodon dactylon	Poaceae	CYDA	P	G	FACU	4	5
Cyperus esculentus	Cyperaceae	CYES	P	G	FACW	2	5
Cyperus odoratus	Cyperaceae	CYOD	A/P	G	FACW+	2	5
Cyperus strigosus	Cyperaceae	CYST	P	G	FACW	2	5
Dactyloctenium aegyptium	Poaceae	DAAE	A	G	N/A	5	
Datura wrightii	Solanaceae	DAWR	A/P	F/SS	N/A	5	8
Daucus pusillus	Apiaceae	DAPU	A	F	N/A	4	4
Digitaria sanguinalis	Poaceae	DISA	A	G	FACU	4	5
Distichlis spicata	Poaceae	DISP	P	G	FACW	2	
Echinochloa colona	Poaceae	ECCO	A	G	FACW	2	8
Echinochloa crus-galli	Poaceae	ECCR	A	G	FACW-	2	8
Eleocharis macrostachya	Cyperaceae	ELMA	P	G	OBL	1	3
Eleocharis montevidensis	Cyperaceae	ELMO	P	G	FACW	2	3
Eleocharis palustris	Cyperaceae	ELPA	p	g	FACW	2	3
Elymus canadensis	Poaceae	ELCA	P	G	FAC	3	6

Genus species	Family	abbr.	Duration	Form	Wetland	WIS	N score
Equisetum laevigatum	Equisetaceae	EQLA	P	G	FACW	2	4
Eragrostis cilianensis	Poaceae	ERCI	A	G	FACU+	4	3
Eragrostis pectinacea	Poaceae	ERPE	A/P	G	FAC	3	3
Eriastrum diffusum	Polemoniaceae	ERDI2	A	F	N/A	5	
Eriochloa acuminata	Poaceae	ERAC	A	G	FACW	2	4
Eriogonum abertianum	Polygonaceae	ERAB	A	F	N/A	5	
Erigeron divergens	Poaceae	ERDI	B	F	N/A	5	3
Eriochloa acuminata	Poaceae	ERAC	A	G	FACW	2	
Eriogonum abertianum	Polygonaceae	ERAB	A	F	N/A	5	
Eriogonum trichopes	Polygonaceae	ERTR	A	F	N/A	5	
Erodium cicutarium	Geraniaceae	ERCI2	A/B	F	N/A	5	3
Eschscholzia californica ssp. Mexicana	Papaveraceae	ESCAM	A/P	F	N/A	5	2
Eschscholzia glyptosperma	Papaveraceae	ESGL	A	F	N/A	5	2
Galium proliferum	Rubiaceae	GAPR	A	F	N/A	5	3
Gaura mollis	Onagraceae	GAMO	A	F	NI	4	
Glandularia bipinnatifida	Verbenaceae	GLBI	A/P	F	N/A	5	
Gutierrezia microcephala	Asteraceae	GUMI	P	SS/S	N/A	5	
Hedosyne ambrosiifolia	Asteraceae	HEAM	A	F/SS	N/A	5	
Helenium thurberi	Asteraceae	HETH	A	F	OBL	1	4
Helianthus annuus	Asteraceae	HEAN	A	F	FAC-	3	8
Helianthus petiolaris	Asteraceae	HEPE	A	F	N/A	5	8
Heliomeris multiflora	Asteraceae	HEMU	P	SS/F	N/A	5	
Heliotropium curassavicum	Boraginaceae	HECU	A/P	SS/F	FACW	2	6
Heterotheca subaxillaris	Asteraceae	HESU	A	F	UPL	5	
Hordeum murinum	Poaceae	HOMU	A	G	NI	5	5
Hymenoclea monogyra	Asteraceae	HYMO	P	SS/S	N/A	5	
Hyptis emoryi	Lamiaceae	HYEM	P	S	N/A	5	
Ipomoea cristulata	Convovulaceae	IPCR	A	V/F	N/A	4	2
Ipomoea hederacea	Convovulaceae	IPHE	A	V/F	FACU*	4	2
Ipomoea purpurea	Convovulaceae	IPPU	A	V/F	UPL	5	2

Genus species	**Family**	**abbr.**	**Duration**	**Form**	**Wetland**	**WIS**	**N score**
Ipomoea ternifolia	Convovulaceae	IPTE	A	F	N/A	4	2
Ipomopsis longiflora	Polemoniaceae	IPLO	A	F	N/A	5	3
Isocoma tenuisecta	Asteraceae	ISTE	P	SS/F	N/A	5	
Juncus bufonius	Juncaceae	JUBU	A	G	OBL	1	4
Juncus mexicanus	Juncaceae	JUME	P	G	FACW	2	3
Juncus torreyi	Juncaceae	JUTO	P	G	FACW	2	3
Lactuca canadensis	Asteraceae	LACA	A/B	F	FACU	4	4
Laennecia coulteri	Asteraceae	LACO	A	F	FACW-	2	
Lappula occidentalis	Boraginaceae	LAOC	A/B	F	N/A	5	7
Lemna gibba	Lemnaceae	LEGI	A	F	OBL	1	8
Lepidium lasiocarpum	Brassicaceae	LELAL	A/B	F	N/A	4	5
Lepidium latifolium	Brassicaceae	LELA	P	F	NI	4	5
Lepidium thurberi	Brassicaceae	LETH	A/B	F	N/A	4	5
Leptochloa dubia	Poaceae	LEDU	P	G	N/A	5	
Leptochloa panicea	Poaceae	LEPA	A/P	G	OBL	1	
Lesquerella gordonii	Brassicaceae	LEGO	A/B/P	F	N/A	5	
Lycium berlandieri	Solanaceae	LYBE	P	S	N/A	5	4
Lythrum californicum	Lythraceae	LYCA	P	SS/F	OBL	1	4
Machaeranthera canescens	Asteraceae	MACA	A/B/P	F	UPL	5	
Machaeranthera tanacetifolia	Asteraceae	MATA	A/B	F	N/A	5	
Malacothrix stebbinsii	Asteraceae	MAST	A	F	N/A	5	
Marrubium vulgare	Lamiaceae	MAVU	P	SS/F	FAC+	3	8
Maurandella antirrhiniflora	Scrophulariaceae	MAAN	P	V/F	N/A	4	
Melilotus alba	Fabaceae	MEAL	A/B/P	F	FACU+	4	4
Melilotus indicus	Fabaceae	MEIN	A	F	FACU+	4	7
Melilotus officinalis	Fabaceae	MEOF	A/B/P	F	FACU+	4	3
Mentzelia multiflora	Loasaceae	MEMU	B/P	F	N/A	5	4
Mimulus guttatus	Scrophulariaceae	MIGU	A/P	F	OBL	1	6
Mirabilis pumila	Nyctaginaceae	MIPU	P	F	N/A	4	
Mollugo verticillata	Molluginaceae	MOVE	A	F	FAC-	3	

Genus species	**Family**	**abbr.**	**Duration**	**Form**	**Wetland**	**WIS**	**N score**
Nama hispidum	Hydrophyllaceae	NAHI	A	F	N/A	5	
Nasturtium officinale	Brassicaceae	NAOF	P	F	OBL	1	7
Nicotiana glauca	Solanaceae	NIGL	P	T/S	FAC	3	6
Nicotiana obtusifolia	Solanaceae	NIOB	A/B/P	F/SS	FACU	4	6
Oenothera primiveris	Onagraceae	OEPR	A	F	N/A	5	4
Opuntia engelmanni	Cactaceae	OPEN	P	S	N/A	5	
Parkinsonia sp.	Fabaceae	PASP	P	T	N/A		
Pectocarya heterocarpa	Boraginaceae	PEHE	A	F	N/A	5	
Penstemon barbatus	Scrophulariaceae	PEBA	P	F	N/A	5	
Phalaris minor	Poaceae	PHMI	A	G	N/A	5	
Physalis acutifolia	Solanaceae	PHAC	A	F	N/A	5	7
Pluchea sericea	Asteraceae	PLSE	P	S	FACW-	2	
Poa bigelovii	Poaceae	POBI	A	G	N/A	5	5
Polanisia dodecandra ssp. Trachysperma	Capparaceae	PODO	a	f	FACU-	4	
Polygonum douglasii	Polygonaceae	PODO	a	f	UPL	5	8
Polygonum lapathifolium	Polygonaceae	POLA	A	F	OBL	1	8
Polypogon monspeliensis	Poaceae	POMO	A	G	FACW+	2	6
Polypogon viridis	Poaceae	POMO	A	G	FACW+	2	
Populus fremontii	Salicaceae	POFR	P	T	FACW	2	6
Portulaca oleracea	Portulaceae	POOL	A	F	FAC	3	7
Proboscidea parviflora	Pedaliaceae	PRPA	A	F	N/A	5	
Prosopis velutina	Fabaceae	PRVE	P	T/S	N/A		
Pseudognaphalium canescens	Asteraceae	PSCA	A/B/P	F	UPL	5	2
Pseudognaphalium luteoalbum	Asteraceae	PSCA	A	F	FAC	3	2
Ranunculus sceleratus	Ranunculaceae	RASC	A/P	F	OBL	1	9
Rivina humilis	Phytolaccaceae	RIHU	P	F/S	N/A	5	
Rumex crispus	Polygonaceae	RUCR	P	F	FACW	2	6
Rumex dentatus	Polygonaceae	RUDE	A/B	F	NO	1	6
Rumex hymenosepalus	Polygonaceae	RUHY	P	F	N/A	3	6
Rumex obtusifolius	Polygonaceae	RUOB	P	F	FACW	2	9

Genus species	**Family**	**abbr.**	**Duration**	**Form**	**Wetland**	**WIS**	**N score**
Salix exigua	Salicaceae	SAEX	P	T/S	OBL	1	5
Salix gooddingii	Salicaceae	SAGO	P	T	OBL	1	5
Salsola tragus	Chenopodiaceae	SATR	A	F	FACU	4	6
Sarcostemma cynanchoides	Asclepiadaceae	FUCYC	P	F/V	FAC-	3	3
Schismus arabicus	Poaceae	SCAR	A	G	N/A	5	1
Schismus barbatus	Poaceae	SCBA	A	G	N/A	5	1
Schoenoplectus acutus	Cyperaceae	SCAC	P	G	OBL	1	6
Schoenoplectus americanus	Cyperaceae	SCAM	P	G	OBL	1	7
Schoenoplectus pungens	Cyperaceae	SCPU	P	G	OBL	1	7
Setaria adhaerens	Poaceae	SEAD	A	G	N/A	4	7
Setaria grisebachii	Poaceae	SEGR	A	G	N/A	4	7
Setaria macrostachya	Poaceae	SEMA		G	N/A	4	7
Setaria vulpiseta	Poaceae	SEVU	P	G	N/A	5	7
Sicyos ampelophyllus	Cucurbitaceae	SIAM	A	V/F	N/A	5	
Sisymbrium irio	Brassicaceae	SIIR	A	F	N/A	5	5
Solanum americanum	Solanaceae	SOAM	A/P	SS/F	FAC	3	7
Solanum douglasii	Solanaceae	SODO	P	SS/F	FAC	3	7
Solanum elaeagnifolium	Solanaceae	SOEL	P	SS/F	N/A	5	7
Sonchus asper	Asteraceae	SOAS	A	F	FACW	2	7
Sorghum halepense	Poaceae	SOHA	P	G	FACU+	4	7
Sphaeralcea angustifolia	Malvaceae	SPAN	P	SS/F	N/A	5	
Sphaeralcea emoryi	Malvaceae	SPEM	P	SS/F	N/A	5	
Sphaeralcea laxa	Malvaceae	SPLA	P	F	NI	5	3
Sporobolus contractus	Poaceae	SPCO	P	G	N/A	4	4
Sporobolus cryptandrus	Poaceae	SPCR	P	G	FACU-	4	4
Sporobolus wrightii	Poaceae	SPWR	P	G	N/A	4	4
Symphyotrichum divaricatum	Asteraceae	SYDI	A/B	F	N/A	3	
Symphyotrichum lanceolatum	Asteraceae	SYLA	P	F	OBL	1	
Tamarix ramosissima	Tamaricaceae	TARA	P	T/S	NI	2	
Tidestromia lanuginosa	Amaranthaceae	TILA	A	F	N/A	5	

Genus species	**Family**	**abbr.**	**Duration**	**Form**	**Wetland**	**WIS**	**N score**
Trianthema portulacastrum	Aizoaceae	TRPO	A/P	F	NI	2	
Typha domingensis	Typhaceae	TYDO	P	F	OBL	1	8
Verbascum virgatum	Scrophulariaceae	VEVI	B	F	N/A	4	5
Verbena gracilis	Verbenaceae	VEGR	P	F	N/A	5	7
Verbesina encelioides	Asteraceae	VEEN	A	F	FAC	3	
Veronica anagallis-aquatica	Scrophulariaceae	VEAN	B/P	F	OBL	1	5
Xanthium strumarium	Asteraceae	XAST	A	F	NI	4	6
Xanthocephalum gymnospermoides	Asteraceae	XAGY	a	f	FACW	2	