Riparian Dynamics: The Ebb and Flow of Ecological Function

RIPARIAN DYNAMICS:
THE EBB AND FLOW OF ECOLOGICAL FUNCTION

by

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DEDICATION

For Brian, who nourishes, energizes, and inspires me.

For Mom, Gary, and Angie, who have nurtured and supported my dreams.

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ABSTRACT

Competition over freshwater resources is increasing at local and global scales. Growing urban and suburban centers utilize surface and groundwater resources to meet municipal, industrial, and agricultural demands, often at the expense of riparian ecosystems. Paradoxically, those same urban centers produce a significant volume of treated effluent that can be reused to restore and sustain riparian systems. Use of effluent as a source of water for the environment raises important questions about the benefits and impacts of effluent on riparian functions and ecosystem services, particularly in the context of climate change and drought conditions. This dissertation addresses knowledge gaps surrounding riparian change and resilience along the effluent-dominated Upper Santa Cruz River in southern Arizona. Appendix A investigates whether the Netleaf hackberry (*Celtis laevigata var. reticulata*) tree can provide accurate information on historic changes in climatic and hydrological conditions. Results indicate that hackberry trees do record climate-related stress in annual ring-width patterns and can therefore provide a historic frame of reference against which to compare current and future changes in riparian conditions. Appendix B documents spatial and temporal patterns of effluent uptake by Fremont cottonwood trees (*Populus fremontii*) through development of a new application for dendrochronology, specifically dendrochemistry. Results show that annual tree rings contain temporally variable concentrations of a micropollutant found only in effluent and may have the potential to record spatial and temporal patterns of effluent dispersion in riparian ecosystems. Appendix C investigates the complex interactions of ecohydrological conditions that led to a riparian mortality event along the Upper Santa Cruz River in 2005. Effluent is shown to contribute to riparian vegetation expansion, but also, due to its consistent delivery of nutrients and water, homogenize the system and ultimately diminish its resilience to perturbations and stress. Results highlight the paradoxical nature of effluent as both a contributor to riparian growth and a potential impediment to riparian function. This paradox can be resolved through a well-defined effluent impact monitoring and assessment program that incorporates historic information as well as current trends to detect significant changes in ecosystem functions and services.

CHAPTER 1: INTRODUCTION

1.1 Problem and Context

Functioning riparian ecosystems in the southwestern United States provide numerous services and benefits to surrounding human populations, including water filtration, groundwater recharge, flood control, and habitat for wildlife (Naiman and Decamps 1997, Naiman et al. 2005, Brauman et al. 2007). In spite of their importance, these systems are under increasing pressure from direct human alteration to the quality and quantity of surface and groundwater (Postel 2000, Malmqvist and Rundle 2002, Lite and Stromberg 2005) and climate change impacts (IPCC 2007). As one mitigation to these threats, municipal wastewater (effluent) can can bolster groundwater-dependent riparian ecosystems (Patten et al. 1998) and play an important role in ecosystem restoration by augmenting streamflow, supporting flora and fauna, and recharging local water tables (Bouwer 2002, Brooks et al. 2006).

While there are many benefits to utilizing effluent for the maintenance of instream flows, there are numerous unresolved ecohydrological issues regarding the release of effluent into groundwater-dependent riparian systems. The full suite of benefits and impacts that effluent has on ecosystem function has yet to be quantified. In addition, there is little knowledge about how native riparian vegetation incorporates and responds to continuous inflows of nutrient-rich effluent. This knowledge gap is particularly compelling within the context of climate variability, prolonged drought, and rising temperatures that are expected to increase freshwater demands and further degrade riparian systems. Ultimately, 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).

The Upper Santa Cruz River in southern Arizona presents an ideal laboratory in which to study the dynamics of an effluent-dominated riparian system and develop tools for monitoring and managing other similar systems. The Nogales International Wastewater Treatment Plant discharges up to 65,109 m^3/day (17.2 mgd) of effluent into the Upper Santa Cruz River. Effluent augments highly variable surface water flows and shallow groundwater tables that support a riparian ecosystem. After several decades of growth and expansion resulting from favorable climate conditions and effluent subsidies, mature riparian trees experienced a sudden and unexpected mortality event in 2005. The die-off stretched for approximately 16 km directly downstream of the Nogales International Wastewater Treatment Plant and affected mainly Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*) trees. This mortality event sparked numerous questions about the health of the riparian ecosystem. What caused the trees to die? Were there signs that the trees were in distress? Can this type of event be avoided in the future?

The three studies in this dissertation employ an interdisciplinary approach to begin answering these questions and examining riparian change in an effluent-dominated system. The first two studies utilize dendrochronological methods to examine the relationship between riparian tree growth, climate factors, and water quality. The third study analyzes these relationships specifically within the context of the die-off and proposes several management options that may aid in avoiding future die-off events in the Upper Santa Cruz River and other effluent-dominated systems.

1.2 Background

1.2.1 Ecosystem Services

Ecosystem services are defined as the conditions and processes through which natural systems support, sustain, and enrich human life (Costanza et al. 1997, Daily 1997, MEA 2005). River systems and riparian vegetation provide important hydrologic services and functions that directly benefit surrounding human populations (Brauman et al. 2007). Working in tandem, riparian vegetation and floodplain lands help to filter and purify effluent-dominated surface water as it infiltrates and recharges groundwater and drinking water supplies (Hancock et al. 2005, Boulton et al. 2008). The roots of riparian plants stabilize soil and reduce erosion from floods and significant rainfall events. Riparian shrubs and trees moderate flood flows and help prevent loss of land due to erosive floods. In addition, functioning riparian systems contribute directly to local economies through ecotourism, recreational opportunities, and property values (Colby and Wishart 2002, Bark et al. 2009).

1.2.2 Climate Change Impacts on Freshwater

Freshwater is the primary ingredient that drives the production of the hydrologic services, yet demands for freshwater fall increasingly within the shadow of changing climate conditions and associated impacts. Climate change predictions are particularly alarming for the southwestern United States. Droughts are expected to increase in frequency and severity (Cook 2004) and a 10-30% decrease in run-off is possible by the year 2050 (Milly et al. 2005). A recent study suggests that the continental interior of the United States will likely experience more extensive and intense drought conditions in the next 50 years than have been seen in the past century of instrumented climate data (Hughes and Diaz 2008). Multi-year droughts, as experienced in the Western United States in the past decade, can significantly diminish ecosystem services delivered by watersheds and are expected to induce large shifts in vegetation distribution, composition, and health in the next 50 years (Allen and Breshears 1998).

1.2.3 Upper Santa Cruz River Riparian Mortality

An example of a shift in vegetation distribution and composition occurred in 2005 on the Upper Santa Cruz River. Sudden and unexpected mortality of Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*) species occurred along an approximately 16 km reach of the Upper Santa Cruz River directly downstream of the Nogales International Wastewater Treatment Plant. While USGS streamflow gauges, groundwater levels, and precipitation data from the area recorded regional drought conditions and lower than average stream flows, a study of aerial photographs and satellite imagery did not indicate that the riparian vegetation was exhibiting physical responses to drought or groundwater decline, such as canopy die-back or leaf senescence (Rood et al. 2000, Amlin and Rood 2003, Pearce et al. 2006). This apparent lack of well-documented drought responses exhibited by the Upper Santa Cruz River riparian corridor suggested a threshold change between the conditions that supported the expansion of the cottonwood/willow riparian forest and the conditions that caused a rapid contraction of cottonwood/willow forest.

1.2.4 The Paradox of Effluent

Climate change and urbanization contribute to increasing competition for freshwater sources. More than 75% of the U.S. population is concentrated in urban areas and that number is expected to increase (Paul and Meyer 2001). Paradoxically, while urban centers quench their thirst with diverted surface water and groundwater pumping that degrades riparian ecosystems, urban centers also produce voluminous amounts of treated wastewater that can be used to restore and maintain riparian systems. Effluent is an increasing component of water management equations, and a recent estimate posits that approximately 7.4% of wastewater is used for public and domestic uses in the United

States, primarily for golf course and park irrigation (Miller 2006). This number just begins to highlight the potential for effluent use in reducing pressure on freshwater supplies and restoring riparian habitat (O'Connor et al. 2008).

However, numerous ecohydrological issues surrounding the influence of effluent on riparian systems remain unresolved. High levels of nutrients in effluent bolster vegetation growth (Marler 2001) but poor water quality could lead to long-term impacts on riparian function and human health (Khetan and Collins 2007). Ensuring that effluent contributes to, rather than degrades, riparian function hinges on an understanding of riparian response to hydrological change, water quality impacts, and climate variation.

1.3 Organization of the dissertation

This dissertation consists of three pre-publication manuscripts that appear as Appendices A, B, and C.

The first manuscript (Appendix A) is entitled "Tree-ring analysis of Netleaf hackberry: Applications of dendrochronology in riparian ecology." This study involved the assessment of the dendrochronological potential of a common riparian tree as a means of providing historic perspective on tree growth response to streamflow, precipitation, and temperature. In support of this research, I created five Netleaf hackberry (*Celtis laevigata* var. *reticulata*) tree-ring chronologies that correspond to site-specific hydrologic conditions along the Upper Santa Cruz River. I then used these chronologies in correlation analyses with publicly available climate data. I wrote the manuscript. My co-authors on this manuscript are David Meko, Julie Wong, and Barron Orr.

The second manuscript (Appendix B) is entitled "Riparian dendrochemistry: Detecting anthropogenic gadolinium in trees along an effluent-dominated desert river." This study employs dendrochemistry methodology to document spatial and temporal dispersion patterns of a micropollutant unique to effluent-dominated waterways. Co-author Paul Sheppard and I collected tree-ring, soil, and dust samples, as well as a portion of the water samples. Water samples were also collected by Tom Meixner, a co-author on the manuscript. I prepared the samples for analysis and the Arizona Laboratory of Emerging Contaminants processed the samples. I analyzed the data and wrote the manuscript. My co-authors on this manuscript are Paul Sheppard, Tom Meixner, and Barron Orr.

The final manuscript (Appendix C) is entitled "Impacts of effluent on riparian resilience." This study is an interdisciplinary examination of the influence of effluent on riparian expansion and contraction. I worked with Miguel Villarreal, a co-author, to create a riparian vegetation map of the Upper Santa Cruz River. Miguel Villarreal analyzed historic riparian conditions. I synthesized previously unpublished water quality data sets and climate data to conduct a comparison analysis with the vegetation data. I applied these data to an analysis of effluent management regimes in the Upper Santa Cruz and wrote the manuscript. My co-authors are Miguel Villarreal, Claire Zugmeyer, Cheryl McIntyre, and Barron Orr.

CHAPTER 2: PRESENT STUDY

The methods, results, and conclusions are presented in the papers appended to this dissertation. The following text summarizes the approach and major findings for each of the three studies that comprise my dissertation research.

2.1 Appendix A

Title: Tree-ring analysis of Netleaf hackberry: Applications of dendrochronology in riparian ecology

(Note: This manuscript will be submitted to Tree-Ring Research)

Climate-induced changes in spatial and temporal patterns in water availability highlight the need for accurate and regionally specific metrics of riparian vegetation change. Numerous scientifically rigorous riparian monitoring protocols and assessment methods are well-established (Richter et al. 1996, Richter et al. 1998, Bragg et al. 2005), however a notable monitoring challenge remains in assessing historic hydrologic patterns that extend beyond the lifetime of streamflow gauges and recorded surveys. This historic perspective is central to understanding how vegetation patterns have responded to variable hydrologic and climate conditions and to determining the upper and lower limits of vegetation viability.

Dendrochronology is a proven and effective tool for examining historic influences of climate on ecosystems and offers insights into how ecosystems may respond to changing climate conditions. While dendrochronology is often utilized in forest and upland systems, potential applications in riparian ecosystems have not been fully established. This study involved the investigation of the dendrochronological characteristics and monitoring applications of the common riparian tree Netleaf hackberry (*Celtis laevigata* var. *reticulata*) to address two primary questions:

1. Can Netleaf hackberry trees in the Upper Santa Cruz River basin be effectively cross-dated and thus be useful for dendrochronological analysis in semi-arid riparian ecosystems?
2. If datable, does hackberry radial growth correlate with climatic variables, thus reflecting this tree's ability to record climatic/water stress?

This study produced the first hackberry chronology in the Santa Cruz River watershed and confirmed that hackberry trees do cross-date effectively. Significant correlations of tree-ring indices with temperature and streamflow suggest that moisture limits hackberry growth and that hackberry record climate-related stress in annual ring-width patterns. This information can be used to help understand how changing climate patterns may impact growth trends and the overall health of riparian species. Given increasing demands on water resources, understanding the impacts of hydrologic regimes on riparian ecosystems may contribute to management decisions about groundwater and instream flows. Furthermore, dendrochronological analysis can provide an integrated riparian health assessment tool to management agencies and conservation organizations.

2.2 Appendix B

Riparian dendrochemistry: Detecting anthropogenic gadolinium in trees along an effluent-dominated desert river

(Note: This manuscript will be submitted to River Research and Applications)

Effluent-dominated streams have unique water quality characteristics that distinguish them from natural streams and raise important questions about the impacts of effluent on riparian function and the degree to which effluent may be recharging drinking water tables. This research documents spatial and temporal patterns of effluent uptake by riparian trees through development of a new application for dendrochronology, specifically dendrochemistry. The rare-earth element gadolinium (Gd), is a known micropollutant in its anthropogenic form that was first used in select medical procedures in 1988 and subsequently discharged via treatment plants into waterways. Riparian trees that utilize effluent-dominated surface water uptake the anthropogenic form of Gd where it remains in annual growth rings. Because anthropogenic Gd was introduced into waterways after 1988, there is a clear presence/absence date stamp that makes Gd an ideal marker for a dendrochronological study investigating the potential for trees to record historic changes in water quality.

This research investigates the impact of effluent on riparian vegetation by addressing four key questions:

1. Is anthropogenic Gd (Gd_{ANTHRO}) present in effluent-dominated surface and groundwater?
2. Do cottonwood trees along the effluent-dominated stream contain Gd_{ANTHRO} in their growth rings in measurable quantities?
3. Do Gd_{ANTHRO} concentrations vary temporally in cottonwood annual rings?
4. Can temporal and spatial variability be correlated with ecohydrologic characteristics of the stream, such as clogging layer dynamics?

Results from this study demonstrate that surface water containing effluent from the Nogales International Wastewater Treatment Plant contains elevated levels of Gd_{ANTHRO} relative to other REEs. Cottonwood trees growing adjacent to the effluent-dominated stream also contain elevated levels of Gd_{ANTHRO} in their annual growth rings. This connection suggests that the cottonwood trees are utilizing effluent at some point during their annual growth cycle and could be relying substantially on effluent during times of drought or when groundwater tables and soil moisture levels are low. Cottonwood trees sampled at a control site also demonstrated elevated levels of Gd_{ANTHRO}. While this site does not receive effluent flows from a treatment plant, it is plausible that wastewater could be recharging groundwater that is transported through geologic faults to the control site.

Evidence of Gd_{ANTHRO} in the annual growth rings of cottonwood trees offers insights into the degree to which riparian species utilize effluent to meet evapotranspiration requirements. Such insights could help inform water management efforts aimed at securing water specifically for environmental needs. Furthermore, if Gd_{ANTHRO} could be developed as a tracer for the presence of effluent in surface water, groundwater, and trees, adaptive policies could be developed to ensure that the quality is effluent is of sufficient quality for both environmental and human uses.

2.3 Appendix C

Impacts of effluent on riparian resilience

(Note: This manuscript will be submitted to Environmental Science and Policy)

This study is framed within the context of the riparian mortality event in 2005 along the Upper Santa Cruz River and focuses specifically on changes in the extent and composition of the riparian forest over time, including an assessment of cottonwood/willow vegetation before and after the 2005 die-off event. Changing riparian vegetation patterns were analyzed within the context of increased effluent subsidies, shifts in climate, and sub-optimal water quality. Five data sets for studying these changes within the Upper Santa Cruz River ecosystem were compiled and analyzed, involving: (1) creation of the first riparian vegetation map along the effluent-dominated reach of the river; (2) reconstruction of historical (1950-2004) vegetation conditions using aerial photography; (3) synthesis of previously unpublished water quality data, including documentation of increased nutrient concentrations; (4) effluent discharge data; and (5) compilations of regionally specific climate information, including changing precipitation and streamflow patterns. Using these data sets, we address three questions:

1. How has riparian vegetation composition and extent varied over time in response to effluent subsidies?
2. How have water quality and climate trends affected the role of effluent subsidies in the system?
3. How have these factors contributed to the 2005 riparian vegetation die-off?

Building from our analysis, we briefly examine how gaps in Arizona's water management framework have enabled effluent subsidies to sustain a riparian area without the necessary adaptive responses to ensure that effluent bolsters the consistent and continued provision of ecosystem services.

The results of this study explain an ecological threshold event between the conditions that supported the expansion of the riparian ecosystem and the conditions that caused a rapid contraction of cottonwood/willow forest on the Upper Santa Cruz River. Vegetation analysis illustrates an increase in extent and density in the riparian corridor in the 1980s and 1990s as a result of effluent subsidies and favorable climate conditions. In the shadow of robust vegetation growth, poor effluent water quality was slowly degrading hydrologic functions. These opposing sets of conditions collided in 2005 and resulted in a cottonwood/willow vegetation die-off event.

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). Understanding how the system is changing and adapting to cross-scale influences will aid in designing monitoring and assessment tools that can ensure that effluent contributes to, rather than degrades, riparian resilience and the provision of riparian ecosystem services.

2.4 Future Research

Three primary areas for further investigation emerge from the research pursued in this dissertation.

2.4.1 Expansion of Hackberry Chronology

Netleaf hackberry trees are ring-porous, with large earlywood pores in multiple columns followed by wavy bands of latewood pores (Hoadley 1990). Ring boundaries separate the latewood of the previous year from the earlywood of the following year, though these boundaries are not consistently well-defined. Narrow rings often do not have any visible latewood, suggesting that in years with unfavorable growing conditions, trees may only develop one or two columns of earlywood vessels. Successive years of unfavorable growing conditions produce consecutive narrow rings which can be difficult to delineate. Widths for earlywood and latewood varied from year-to-year within individual cores, though the pattern of variation within trees did correlate across trees. However, I did observe an inconsistent but notable anomaly in the latewood of some wide rings. In these rings, the wavy bands within the latewood would align to form a vertical line that at first glance appeared to be a ring boundary, but upon closer inspection did not contain signature earlywood pores. Observations suggest that these false ring lines (intra-annual ring boundaries) lines were relatively consistent across trees within a chronology. False rings can provide information on the dynamics of seasonal drought in riparian ecosystems and cottonwood false ring patterns have been used in drought studies on the San Pedro River in southeastern Arizona (Morino 2008). Studying cottonwood false rings in combination with potential hackberry false rings could offer further insights into seasonal changes in ecohydrological conditions that impact riparian health and function.

2.4.2 Deepening of Dendrochemistry Studies

Water quality concerns drive negative public perceptions about effluent use (Brooks et al. 2006) and are a primary research trajectory (Corwin and Bradford 2008).

Dendrochemistry has significant potential for tracing changing water quality conditions in effluent-dominated systems. Future research on Gd_{ANTHRO} concentrations within other riparian species such as Velvet ash (*Fraxinus velutina*) and Netleaf hackberry (*Celtis laevigata* var. *reticulata*) would offer additional insights into the spatial gradient of effluent utilization and temporal differences in Gd_{ANTHRO} concentrations. Investigating temporal and spatial patterns of other elements, metals, and/or micropollutants in effluent-dominated streams in the southwest would further contribute to an understanding of water quality patterns. More information on the impacts of effluent quality on the chemical composition of tree rings can be a useful monitoring tool to evaluate the spatial and temporal patterns of effluent use in riparian trees and to identify high-frequency changes in surface water quality.

2.4.3 Quantifying Ecosystem Services

The degree to which effluent can be effectively utilized to maintain riparian ecosystems hinges on the degree to which the public values the effluent. Public values will be determined by the reliability and extent to which effluent can help or hinder riparian health and resilience. A robust and thorough ecological monitoring program capable of tracking annual changes in ecological functions related to the provision of specific ecosystem services could assist in adaptively responding to changes in riparian function. Indicators of riparian function that can be measured on short (annual) and long-term intervals need to be well defined. These functional indicators can then be linked to the production of ecosystem services and can help quantify how change impacts the system. Ultimately, an ecosystem services operating framework that integrates social values (as expressed in economic terms) and ecological function (in the provision of services that can be measured and valued) may offer an opportunity to maintain the resilience of the system.

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APPENDIX A -- TREE-RING ANALYSIS OF NETLEAF HACKBERRY: APPLICATIONS OF DENDROCHRONOLOGY IN RIPARIAN ECOLOGY

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A.1 Abstract

Current global climate change predictions present uncertainties regarding the variability of river flows in the southwestern United States that could lead to escalating ecosystem stress throughout the region. These predictions reinforce a growing need for a more adaptive approach to management of river systems. Dendrochronology is a proven and effective tool for examining historic influences of climate on ecosystems and offers insights into how ecosystems may respond to changing climate conditions. While dendrochronology is often utilized in forest and upland systems, potential applications in riparian ecosystems have not been fully established. This study investigates the dendrochronological characteristics and monitoring applications of the common riparian tree Netleaf hackberry (*Celtis laevigata* var. *reticulata*). The study was completed in the semi-arid Upper Santa Cruz River watershed in southern Arizona. The Upper Santa Cruz River is characterized by a cascading series of shallow sedimentary groundwater basins and a roughly 64 kilometer (km) riparian forest comprised of signature southwestern United States riparian tree species. Results from the study confirm that hackberry trees do cross-date effectively and growth rates correlate with stream flow and with maximum and minimum temperature patterns. This information can be used to help understand how changing climate patterns may impact growth trends and the overall health of riparian species. Given increasing demands on water resources, understanding the impacts of hydrologic regimes on riparian ecosystems could contribute to management decisions about groundwater and instream flows. Furthermore, dendrochronological analysis can

provide a new and integrated riparian health assessment tool to management agencies and conservation organizations.

Keywords: Dendrochronology, Upper Santa Cruz River, Drought, Climate Change, Ecological Monitoring

A.2 Introduction

Recent climate change scenarios for freshwater resources highlight uncertainties about the timing and magnitude of river flows in the southwestern United States that could lead to escalating ecosystem stress throughout the region (Milly et al. 2005, IPCC 2007). Managing river systems is becoming increasingly complex due to human impacts, multiple and competing water needs, and climate variability (Dudgeon et al. 2006, Poff 2009). Climate warming in the southwest is predicted to impact hydrologic cycles and aridity conditions that may induce large shifts in vegetation distribution, composition, and health in the next 50 years (Allen and Breshears 1998, Cook 2004).

Human-induced and irreversible changes to river ecosystems are particularly noteworthy because they call into question our previous assumptions and perceptions that ecosystems were inherently stable and that change was possible to control (Milly et al. 2008). We now know that river systems are simultaneously complex and adaptive, but are nonetheless vulnerable systems (MEA 2005). They do not respond to change in a smooth and linear manner, rather stress can cause a system to shift from an outwardly stable state to an alternate state that may be undesirable and could be difficult, if not impossible, to reverse (Peters et al. 2004).

Possible climate-induced shifts on river flows highlight the need for accurate and regionally specific metrics of riparian vegetation change in the past in response to climate and for improved understanding of how riparian vegetation responds to climate factors (e.g., precipitation, temperature, floods, and droughts). Numerous scientifically rigorous riparian monitoring protocols and assessment methods are well-established (Richter et al. 1996, Richter et al. 1998, Bragg et al. 2005), however a notable monitoring challenge remains in assessing historic hydrologic patterns that extend beyond the lifetime of streamflow gauges and recorded surveys. This historic perspective is central to understanding how vegetation patterns have responded to historic hydrologic and climate conditions and to determining the upper and lower limits of vegetation viability.

While dendrochronology is often utilized to illuminate historical ecosystem perspectives in forest and upland ecosystems, its potential for riparian monitoring and conservation has not yet been fully established. This is largely due to the fact that the response of riparian trees to moisture variations is complicated by various factors, including competition, flooding, and anthropogenic modification of the habitat (Clark 1987, Meko 1998). Furthermore, research in riparian areas is often constrained by the lack of instrumented data on historical flood patterns, streamflow rates, and groundwater levels and the corresponding impacts of hydrologic dynamics on ecological functions. In response to this limitation in riparian dendrochronology, this study explores the feasibility of using a common riparian tree, the Netleaf hackberry (*Celtis laevigata* var. *reticulata*) to augment riparian monitoring techniques by providing a historical perspective of climate influences on riparian vegetation.

The Netleaf hackberry is a small deciduous shrub to small tree in the elm family (*Ulmaceae*). Hackberry trees are widely distributed throughout semi-arid regions and riparian forests in the western United States and can be found at elevations ranging from 200-2000 m (DeBolt and McCune 1995). Hackberry trees are typically found growing in closed canopy forests, or bosques (Spanish for "woodland") with other dominant riparian tree species such as Velvet mesquite (*Prosopis velutina*) and Arizona walnut (*Juglans major*) (Stromberg et al. 1993). Like Velvet mesquite, Netleaf hackberry is a facultative riparian species, meaning that it fulfills its water and evapotranspiration demand by utilizing both groundwater and soil moisture (Stromberg et al. 1996, Naiman et al. 2005).

Relatively little is known about the ecology of the hackberry or its dendrochronological applications. While some studies have focused on the ecology and range of the hackberry and have employed ring counts for age estimates (DeBolt and McCune 1995), there has only been one dendrochronological study using cross-dated hackberry specimens (Salzer et al. 1996).

(Salzer et al. 1996) examined the relationships between climate and hydrology on hackberry growth in the Grand Canyon along the Colorado River. They demonstrated the utility of hackberry for floodplain or flood-zone dendrochronological studies. This utility is due in part to clear and distinct ring boundaries, the rareness of missing and false rings, an adequate mean series inter-correlation, and a clear relationship between climatic variables and ring-width index. This study suggests potential use of hackberries for dendrochronological analysis in studying riparian vegetation changes in response to climatic variation and anthropogenic disturbances throughout the southwestern United States. Whether the dendrochronological strengths of hackberries along the Colorado River can be generalized to other climatic and hydrologic regimes remains an open question. Building off of findings from the Grand Canyon study, this paper addresses two primary questions. (1) Can Netleaf hackberry trees in the Upper Santa Cruz basin be effectively cross-dated and thus useful for dendrochronological analysis in semi-arid riparian ecosystems? (2) If datable, does hackberry radial growth correlate with climatic variables (thus reflecting this tree's ability to record climatic/water/temperature stress)?

A.3 Methodology

A.3.1 Study Area

The Upper Santa Cruz River (USCR) is a unique and regionally significant watershed in the southwestern United States that hosts tremendous ecological diversity and a mosaic of cultures and history (Marshall et al. 2004). Stretching across southern Arizona and the northern portion of the Mexican state of Sonora, the USCR is the only river to cross the U.S./Mexico border twice. From the high desert grasslands of southeastern Arizona, it flows southwards into northern Sonora, then back into Arizona where it continues for another 120 miles before intersecting with the Gila River (Figure 1). This study focuses on a 64 km stretch of river between the U.S./Mexico border and the Santa Cruz County/

Pima County line.

As the distinguishing geographic feature of the study area, the Upper Santa Cruz River supports a roughly 64 km riparian forest comprised of signature riparian tree species such as Fremont cottonwood (*Populus fremontii),* Goodding's willow *(Salix gooddingii),* Velvet ash (*Fraxinus velutina*), Velvet mesquite (*Prosopis velutina*), Arizona walnut (*Juglans major*) and Netleaf hackberry (*Celtis laevigata* var. *reticulata*). The river is characterized by a series of shallow and undulating micro-basins that together form the underlying floodplain aquifer. Groundwater levels in the USCR basin have varied over time in response to climate conditions and human use patterns. Due to the shallowness of the aquifer and the permeable nature of the alluvium, the water table is very sensitive to climatic changes, rising quickly during heavy precipitation events and depleting rapidly during dry periods (Nelson 2007).

Recharge from the stream into groundwater tables is tightly linked to precipitation patterns. The year 2000 was a flood-dominated year with 62 million m^3 (50,000 acre-feet (af)) recharge, while 2002 was the start of the drought and recharge was less than 25 million m^3 (20,000 af) (Nelson 2007). Surface flow in the river is ephemeral and intermittent from the headwaters, through Sonora, and into Arizona for about 16 km. At the confluence of Sonoita Creek and the USCR, a perennial reach of the river runs north for about 48 km as a result of daily effluent discharges from the Nogales International Wastewater Treatment Plant (NIWTP).

The NIWTP began operation in the 1970's and reached its current discharge capacity of 65,109 m^3/day (17.2 mgd) in the mid-1990's. Due to groundwater pumping to support growing municipalities and agricultural operations, the once dense riparian forest along the river receded by the 1950s. Daily inflows of effluent from the NIWTP have revived the riparian ecosystem and almost 600 species of vertebrates and invertebrates now depend upon the river system for either temporary or permanent habitat (Powell 2004). The Arizona Department of Water Resources notes that since effluent subsidies began in 1972, the discharge of treated effluent into the channel resulted in an approximately 0.8 meter average increase in groundwater levels for wells located downstream of the NIWTP (Corkhill and Dubas 2007). A corresponding analysis of riparian vegetation patterns over time suggests that riparian vegetation has increased in density and extent due to the introduction of effluent into the USCR system. Recent synthesis of historic aerial photographs and current satellite imagery shows that floodplain lands receiving direct effluent subsidies have experienced a rapid increase in the area of mature riparian forests from 1984 to 2004 (Villarreal 2009).

A.3.2 Sample Collection

Collections of Netleaf hackberry (*Celtis laevigata* var. *reticulata*) were made from living trees within the USCR watershed in July 2007 and April 2008 (Figure 1). Samples were collected using standard increment core collecting techniques (Stokes and Smiley 1968). Five sites were selected for sampling that were representative of the hydrological conditions along the Santa Cruz River and two primary tributaries. Descriptions of each site are included in Table 1.

Trees within the 100 year floodplain and clustered in mesquite/hackberry bosques were targeted for sampling. Care was taken to select trees that rely on natural sources of water (precipitation and groundwater) and to avoid sampling from trees that could draw water from irrigated pastures or landscaping.

A.3.3 Sample Preparation

Lab methods followed standard procedures (Stokes and Smiley 1968). Samples were air dried, mounted, and sanded on the transverse surface to reveal individual rings. Each sample was visually inspected with a microscope and cross-dated through a combination of skeleton-plotting and visual matching patterns of narrow and wide rings (Douglas 1941). Dated ring-widths were measured to the nearest 0.01mm for each sample using standard procedures (Stokes and Smiley 1968). In addition to measuring the width of annual rings, measurements of both earlywood and latewood were taken for all cores.

Cross-dating accuracy was checked by cross-correlation analysis using the dendrochronological program COFECHA (Holmes 1983, Grissino-Mayer 2001).

A.3.4 Chronology Data

The dendrochronological statistics program COFECHA endorsed cross-dating at each site (Table 2). The between-tree intercorrelation (the degree to which ring-width patterns correlate across trees within a single site) for each of the five sites ranged between 0.54 and 0.7. As a general rule, mean between-tree correlation of standard indices for high-quality precipitation-sensitive conifer tree-ring sites in the southwestern United States exceeds 0.5. For example, series intercorrelation for a recent Colorado River reconstruction (Meko et al. 2007) exceeds 0.60 for 10 of 11 chronologies, and reaches 0.77 for the chronology with the strongest common signal. Therefore, the between-tree intercorrelations for the USCR hackberry chronologies were sufficient to support cross-dating and were within the same ranges as the intercorrelations found in the Grand Canyon study (Salzer et al. 1996).

All ring width series were processed using the ARSTAN program (Cook 1985) to de-trend the ring-width series and perform autoregressive modeling. Each raw ring-width measurement series was standardized to remove long-term growth trends attributed to increasing tree age and size using a linear regression line with either a negative or zero slope (Cook et al. 1990). Initially, ring-width series were standardized using a modified negative exponential curve. However, fitting this curve to the data was not possible for the majority of ring-width series and a linear regression line was selected for consistency. Tree-ring indices of growth were calculated as the ratio of the raw ring width measurement to the fitted trend-line value for each year (Fritts 1976). Individual ring-index values were averaged together using the arithmetic mean to create five site chronologies (Cook 1985, Cook and Peters 1997).

The dendrochronological program ARSTAN produces a set of mean index chronologies from all detrended series within a site that include a standard chronology (arithmetic mean), residual chronologies (low-order autocorrelation, high-frequency variation removed), and an "ARSTAN" chronology (Cook 1985). All analyses in this study were based on the standard rather than auto-regressive-residual site chronologies to retain low order autocorrelation in the chronologies.

A.3.5 Climate Analysis

A correlation analysis was conducted between each site chronology and monthly climatic variables including monthly precipitation, mean monthly temperatures, and minimum/ maximum mean monthly temperatures. Temperature and precipitation data were obtained from the Western Regional Climate Center (www.wrcc.dri.edu) for stations in Nogales and Tumacácori. Climate data for Nogales was combined from three stations that operated during consecutive, but not overlapping, time periods. Climate data from

Nogales begins in 1915 and data from Tumacácori dates from 1946. Streamflow data was obtained from the United States Geological Survey (USGS) Real-Time Water Data website (waterdata.usgs.gov/nwis/rt) for the Nogales and Tubac gages. Nogales streamflow data begins in 1915 and Tubac streamflow data begins in 1995.

The mean monthly climate variables were calculated for the hydrologic water year beginning in October of the previous growth year and ending in September of the current growth year. The water year was used for the analysis because growing season ring widths can be influenced by climatic events in the latter portion of the previous growing season (Fritts 1976). In addition, streamflow and precipitation data were further delineated and analyzed for three precipitation seasons: arid fore-summer (April - June), summer (July-September) and winter (November-March) (Sheppard et al. 2002).

A.4 Results and Discussion

A.4.1 Chronology

Five chronologies were developed for *Celtis laevigata* var. *reticulata* within the Upper Santa Cruz River watershed (Figures 3-7). The shortest chronology is Sopori Wash at 76 years (1932-2007) (Figure 6) and the longest is Sonoita Creek at 104 years (1904-2007) (Figure 6 & Table 2). The hackberry trees sampled in the USCR are several decades younger than the trees sampled in the Grand Canyon study (Salzer et al. 1996), which may be attributed to differences in the hydrologic setting, climate regime, and land-use patterns. Hackberry trees in the Grand Canyon are influenced by regulated flows from dams, a dominant winter precipitation season, and subsist in rocky soil (Carothers and Brown 1991). The USCR watershed has a semi-arid climate defined by mild winters and hot summers. The watershed experiences a bi-modal rainfall pattern that leads to fluctuating streamflow regimes and enhances the responsiveness of the basin to climatic variations. Winter precipitation is dependent on the southern reaches of large, synoptic-scale cyclonic storms arising in the North Pacific Ocean and the summer monsoon season (late June through September) is driven by convective thunderstorms (Adams and Comrie 1997, Sheppard et al. 2002). Land-use patterns also impact the growth patterns of riparian vegetation. Each of the sites are located either within or adjacent to historic agricultural operations that cleared mesquite bosques to accommodate agricultural fields. Repeat photography has shown that the riparian forest overtook retired fields and increased from 1930 through 1995 (Webb et al. 2007). Riparian vegetation also increased in response to significant flood events in 1977, 1983, and 1993 that recharged the shallow aquifers underlying the river.

Netleaf hackberry trees are ring-porous, with large earlywood pores in multiple columns followed by wavy bands of latewood pores (Figure 8) (Hoadley 1990). Ring boundaries separate the latewood of the previous year from the earlywood of the following year, though these boundaries are not consistently well-defined. Narrow rings often do not have any visible latewood, suggesting that in years with unfavorable growing conditions, trees may only develop one or two columns of early wood vessels. Successive years of unfavorable growing conditions produce consecutive narrow rings that can be difficult to delineate.

Widths for earlywood and latewood varied from year-to-year within individual cores, though the pattern of variation within trees did correlate across trees. The authors did observe an inconsistent but notable anomaly in the latewood of some wide rings. In these rings, the wavy bands within the latewood would align to form a vertical line that at first glance appeared to be a ring boundary. Observation suggests that these false ring boundary lines were consistent across trees within a chronology, but further research is warranted to confirm this observation.

Mean sensitivity, the average relative difference in width from one ring to the next (Fritts 1976), was calculated as one indication of the presence of high-frequency variance (Strackee and Jansma 1992, Grissino-Mayer 2001). Each of the five series showed values above 0.3 for mean sensitivity. High-frequency variance is generally represented by wavelengths of eight years or less and could include year-to-year ring-width variations and short-term variations in climate (Fritts 1976). In regions where climate is strongly limiting mean sensitivity and autocorrelation would be inversely related, such that high mean sensitivity and low autocorrelation both suggest the presence of high-frequency variance in ring width (Fritts and Shatz 1975). Notably, autocorrelation values for each of the five USCR sites were also high (r > 0.35) and thus indicative of more low-frequency and multi-decadal variance.

The autocorrelation plots for each site chronology also reveal persistence patterns in indices of annual ring width (Figures 2-6). Autocorrelation measures the association between two ring-widths lagged in time over ten years (ten lags) (Fritts 1976). The autocorrelation coefficient represents the association of one year in a time series with previous years and can range from +1 (perfect, direct agreement) to -1 (perfect, indirect agreement). Values of 0 indicate that the two years are completely independent of one another. Tumacácori and Calabasas autocorrelation decays in a fashion typical of time series with short-term persistence, with high autocorrelation at lag 1 and declining correlation at higher lags. The decay pattern for Sopori is characteristic of a series with negative first-order autocorrelation, though the lag-1 coefficient is barely significant. This autocorrelation pattern reflects the tendency of the series to be on opposite sides of the mean in adjacent years (Figure 6c). The remaining three chronologies have less definitive autocorrelation patterns, though only Buena Vista is judged random.

The statistical suggestion of both low- and high-frequency variance in the chronologies could be indicative of the highly dynamic nature of riparian ecosystems, particularly on the USCR. As a groundwater-dependent system, riparian vegetation along the USCR is responsive to precipitation, streamflow, and groundwater. Underlying the USCR are four narrow and shallow groundwater sub-basins comprised mainly of Younger Alluvium that are bounded by more consolidated sediments in the Older Alluvium and the Nogales Formation (ADWR 2000). The Younger Alluvium consists of unconsolidated sand with significant hydraulic conductivities that yields water easily; consequently, it is the most productive and widely used aquifer in the region. Due to the properties of the Younger Alluvium, the sub-basins are very responsive to droughts and floods. However, this responsiveness also means that the sub-basins can be drawn down quickly as a result of groundwater pumping and during times of drought, when the riparian vegetation relies upon groundwater to meet evapotranspiration requirements. The riparian vegetation is therefore dependent upon frequent flood events to recharge groundwater tables and is susceptible to impacts on lowered water tables from groundwater pumping and drought. Three of the chronologies (Buena Vista, Calabasas County Park, and Sopori Wash) are developed from trees that rely exclusively on precipitation events and groundwater for their water needs. All three sites have been impacted to varying degrees by groundwater pumping which has altered riparian vegetation distribution. The Sonoita Creek chronology is based on trees that are located downstream of Lake Patagonia Dam and receive monthly pulses of streamflow. The Tumacácori chronology is developed from trees located downstream of the Nogales International Wastewater Treatment Plant (NIWTP) which discharges 15 million gallons per day of treated municipal effluent into the stream. While the hackberries are located within a mesquite forest that is elevated above the floodplain by 2-3 meters, it is likely that they are tapping into groundwater tables that are recharged in part by effluent (Corkhill and Dubas 2007, Nelson 2007).

A.4.2 Correlation Analysis

The correlation analysis between climate variables and the master chronologies from each site reveals interesting, though inconsistent, patterns that reinforce the confounding impacts of multiple hydrologic influences on the high statistical values for mean sensitivity and autocorrelation. Correlation plots for each of the five sampling locations showing the relationship between ring-width indices and climatic variables are displayed in Figures 8-15.

A.4.3 Temperature Correlation

The correlation analysis for temperature was completed at each of the four sites for mean monthly temperatures (mean temps), as well as mean monthly maximum (mean max temps) and minimum temperatures (mean min temps). The analysis reveals significant (α=0.01) negative correlation of temperature with site chronology at two sites. The negative correlations found for June mean temps and June mean-max temps at Tumacácori and Sopori (Figures 13 & 15) could reflect growth stress from increased rates of evapotranspiration. Increased rates of evapotranspiration could be particularly stressful for the hackberry forest at Sopori since the trees rely upon groundwater tables when soil moisture is low and the groundwater tables underlying Sopori Wash have been dropping since 1995 (PAG 2005).

A.4.4 Streamflow Correlation

The correlation analysis for streamflow was completed only for Buena Vista, Calabasas, and Tumacácori since streamflow information was not available for the other two sites. The Nogales USGS streamflow gage (Buena Vista and Calabasas) dates from 1930-2005 while the Tubac USGS Gage (Tumacácori) was installed in 1995 and the first complete year was 1996. Another USGS Gage is located just north of the confluence of Sopori Wash and the Santa Cruz River, but its data are considered inaccurate because flow in an overflow channel around the gaging station has not been historically measured (Webb and Betancourt 1992).

Positive correlation relationships were strongly evident at Buena Vista ($r = 0.36$) and Calabasas ($r = 0.57$) for the arid fore-summer months of April - June (Figures 9 and 11). This positive correlation between April/May streamflow and tree growth coincides with the start of the growth season for hackberry trees. Hackberry trees leaf out the last week in March in the USCR basin and water availability then is critical to support new leaf and tree growth. Buena Vista and Calabasas are located along the ephemeral portion of the USCR and the stream flows and groundwater tables are recharged only during precipitation events. Flow events during the arid fore-summer would therefore provide crucial recharge to groundwater basins that would support hackberry growth.

Interestingly, streamflow is negatively correlated with ring-width indices at Tumacácori during both the arid fore-summer months (April - June) and the first two-thirds of the summer rain season (July and August). This negative relationship could be reflective of the presence of a clogging layer that limited exchange between groundwater and surface water in the years 2002-2005. Elevated levels of nitrogen in the effluent have been shown to foster algae growth on the bottom of the stream channel (Hancock 2002). During drought conditions or in the absence of multiple floods within the summer season (Treese 2008), abundant algae growth can develop into a clogging layer that prevents surface and groundwater mixing. As a result stream flow is confined to the main stream channel and becomes disconnected from riparian roots. Since streamflow is not infiltrating into water tables, flow amounts increase while groundwater levels simultaneously drop. This condition overlaps with the onset of a severe multi-year drought in 2002 that has impacted riparian and upland vegetation throughout the southwest (Breshears et al. 2005, Gitlin et al. 2006) and further reduced groundwater recharge. This confluence of events could explain the negative correlation between increased streamflow and reduced hackberry growth.

A.4.5 Precipitation Correlation

Precipitation is positively correlated with ring-width indices at all sites. The lack of a stronger correlation may reflect the complex hydrologic feedback cycles between riparian vegetation growth and climatic factors. Given the multiple interacting hydrologic conditions in a riparian system, the precipitation signal may be reflected through other variables. For example, precipitation may be reflected as the primary driver for streamflow, which recharges groundwater tables that directly support riparian vegetation. Ideally this hypothesis could be tested through a correlation analysis with groundwater levels over time, however due to a paucity of consistent temporal and spatial data for groundwater levels, a correlation analysis could not be performed for this study.

A.5 Conclusion

Netleaf hackberry shows solid dendrochronological potential for the USCR specifically and more generally for riparian ecosystems in the southwestern United Sates. Hackberry is a common riparian tree species and is consistently found growing within mesquite bosques along the main stem of the USCR and its tributaries. Hackberry has numerous qualities which enable it to be used for dendrochronological investigations, including clear annual ring structure and cross-dating at hydrologically distinct sites. Significant correlations of tree-ring indices with temperature and streamflow suggest that moisture limits hackberry growth and that hackberry records climate-related stress in annual ring-width patterns. Notably, hackberry chronologies did not correlate strongly with precipitation, which may be an indication of the complex feedback cycles and connections between riparian vegetation growth and multiple hydrologic variables such as streamflow, groundwater, and high temperatures that increase evapotranspiration rates. Disentangling the multiple ecohydrologic variables that drive riparian function remains a research challenge.

While the chronologies developed for this study were relatively short (<105 years), it may be possible to find and utilize older trees (> 105 years) in bosques that have not been disturbed within the last century. Hackberry chronologies could be complemented by dendroecology studies on upland species that may record variable precipitation patterns more effectively. In addition, hackberry dendrochronology may also contribute to conifer-based streamflow reconstructions as a predictor of high-runoff years or as an indicator of variable shallow groundwater conditions (Salzer et al. 1996, Shamir et al. 2007).

The degree to which hackberry trees can represent the hydrological history of the entire riparian ecosystem remains an open question. Hackberry trees have been observed to tolerate harsh water-stressed environments and can re-sprout quickly following disturbances (DeBolt and McCune 1995), so they may be an especially hardy representative of ubiquitous riparian tree species. Future dendrochronological studies should include other riparian species such as Arizona walnut (*Juglans major*) or Velvet ash (*Fraxinus velutina*) to compare with hackberry chronologies.

Overall, the level of historic physiological detail provided by dendrochronology, used in combination with broad scale studies on riparian health, can lend new insights into annual and long-term responses of vegetation to ecohydrological influences in river basins. With increasing demands on water resources, understanding the impacts of hydrologic regimes on riparian ecosystems will inform management decisions about groundwater and instream flows. Furthermore, dendrochronological analysis can provide a new and integrated riparian health assessment tool to management agencies and conservation organizations endeavoring to adapt to and monitor the impacts of climate change.

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A.8 Figures

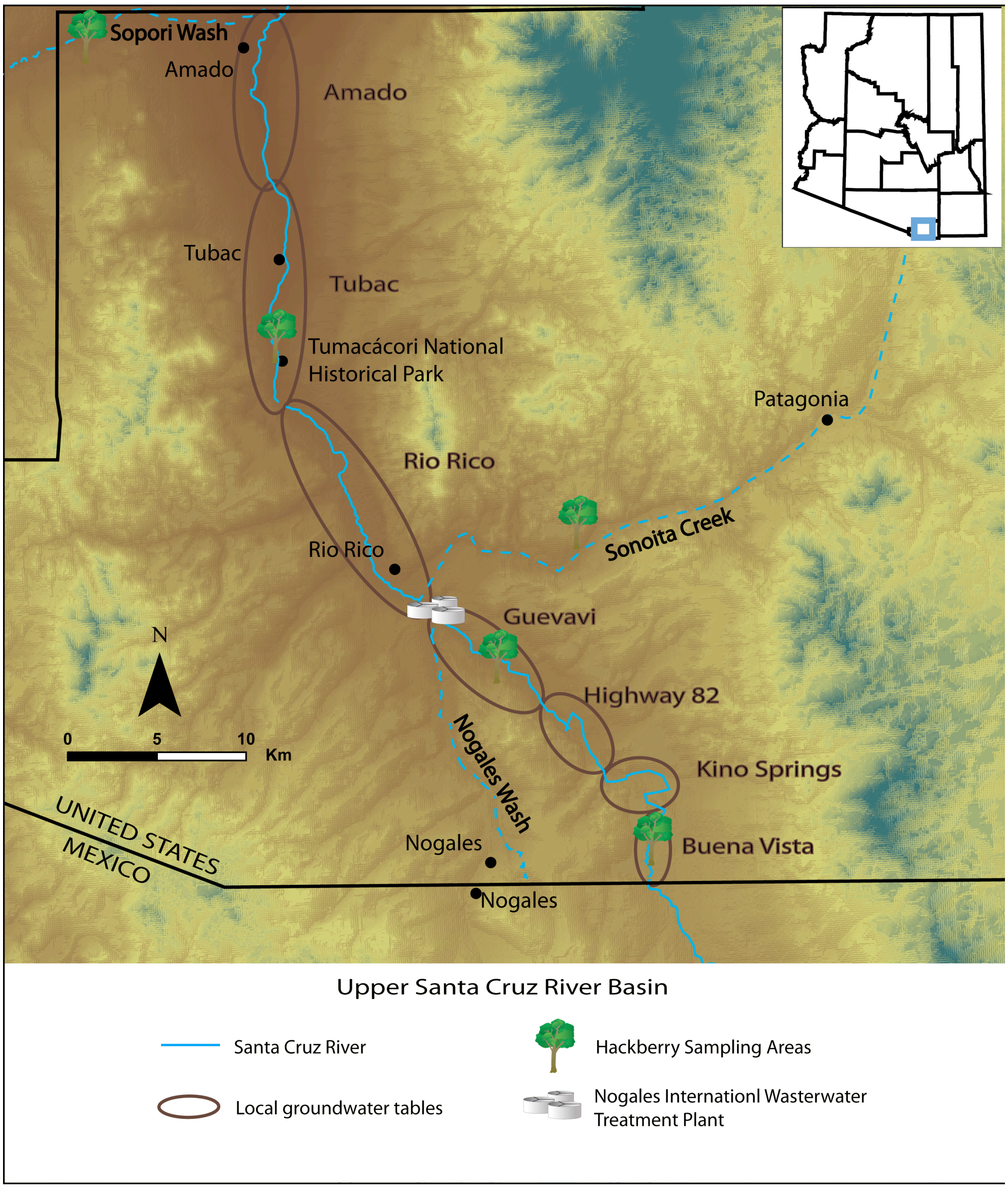


Figure A1. Map of the Upper Santa Cruz River Watershed, including *Celtis laevigata* var. *reticulata* sampling locations.

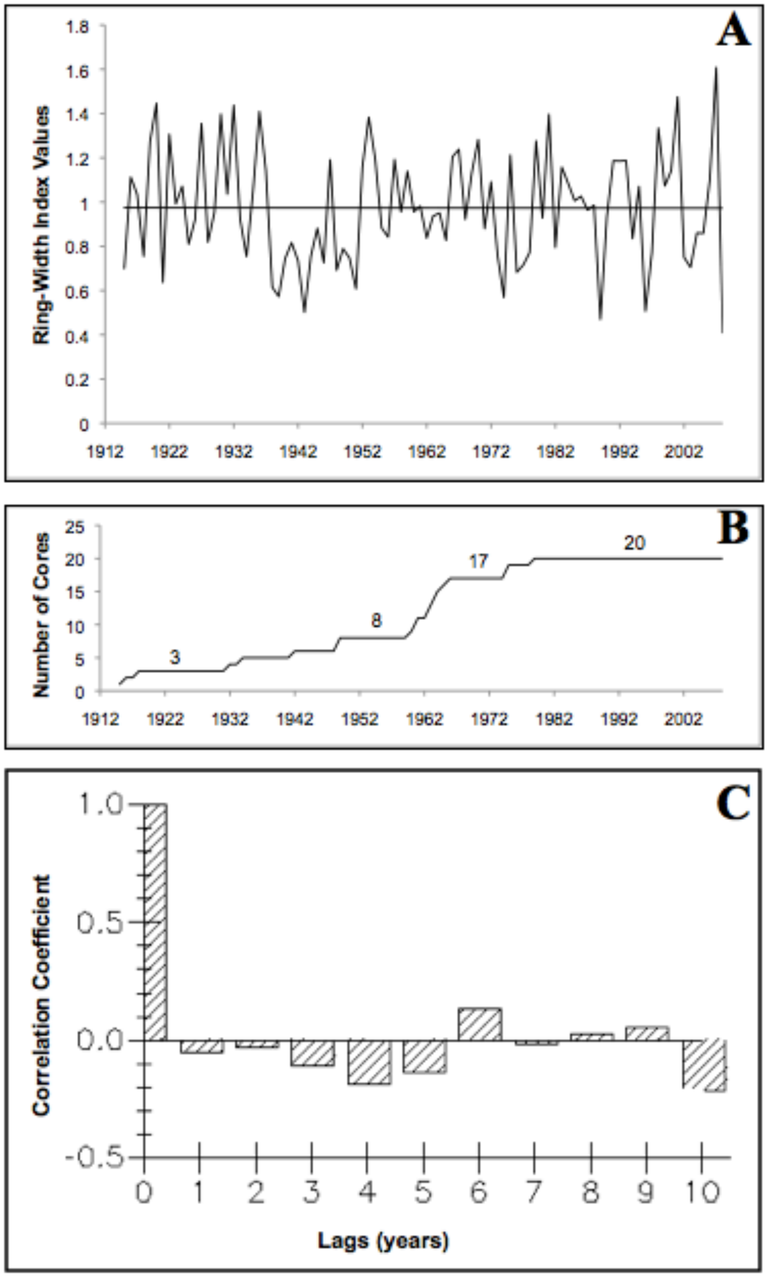


Figure A2. Buena Vista [A] standard chronology, [B] number and distribution of cores within the standard chronology, and [C] autocorrelation coefficients with a lag of ten years.

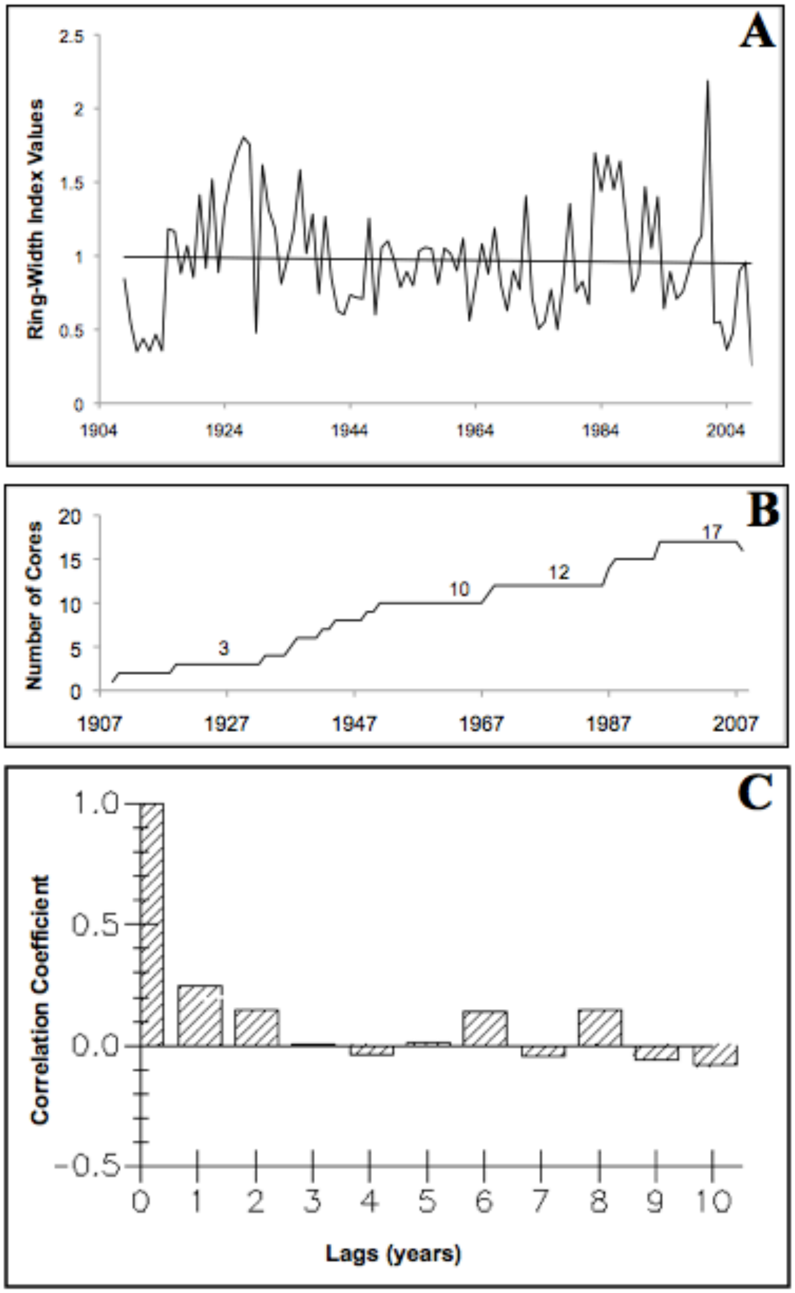


Figure A3. Calabasas [A] standard chronology, [B] number and distribution of cores within the standard chronology, and [C] autocorrelation coefficients with a lag of ten years.

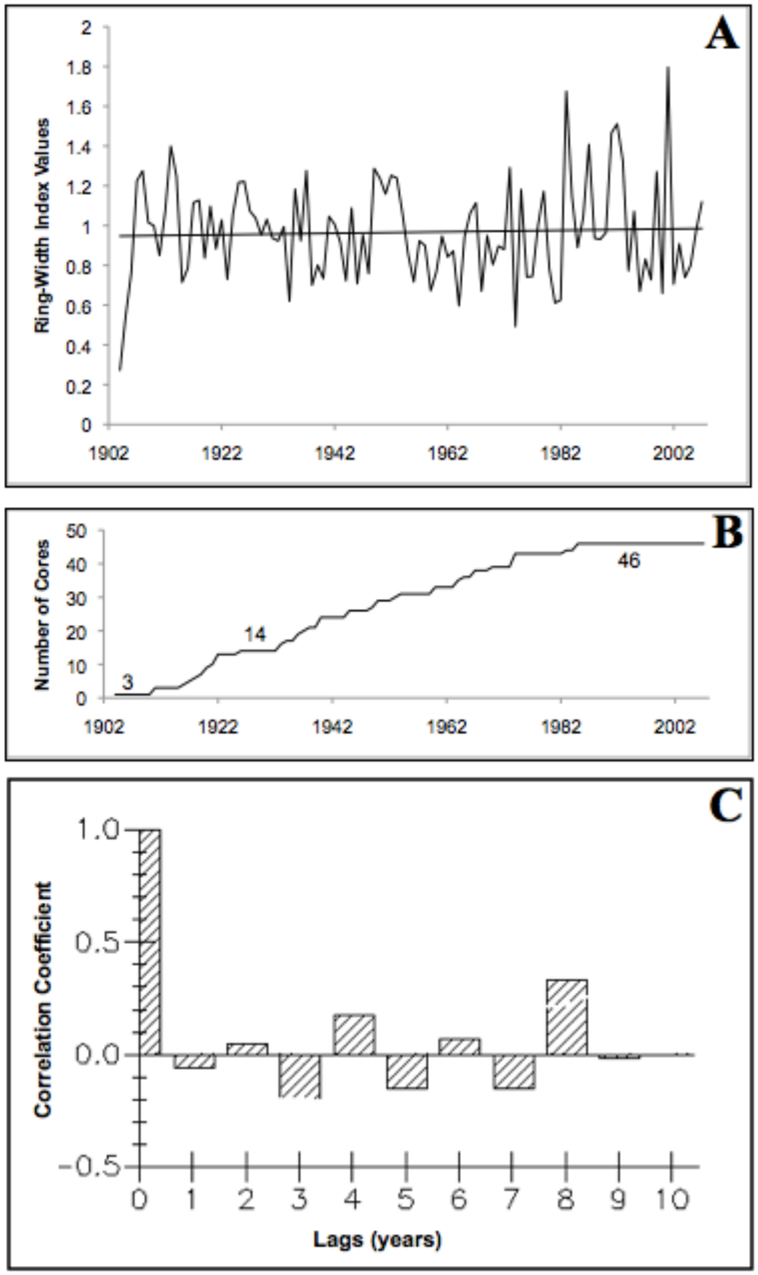


Figure A4. Sonoita Creek [A] standard chronology, [B] number and distribution of cores within the standard chronology, and [C] autocorrelation coefficients with a lag of ten years.

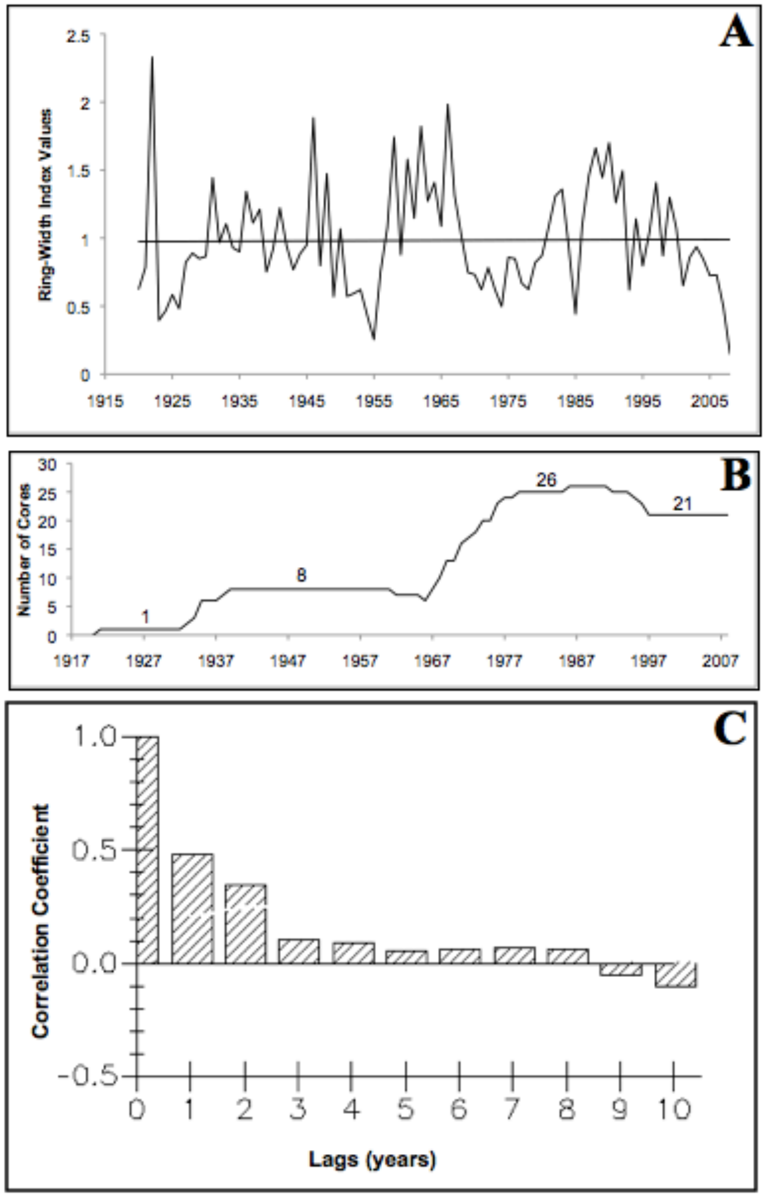


Figure A5. Tumacácori [A] standard chronology, [B] number and distribution of cores within the standard chronology, and [C] autocorrelation coefficients with a lag of ten years.

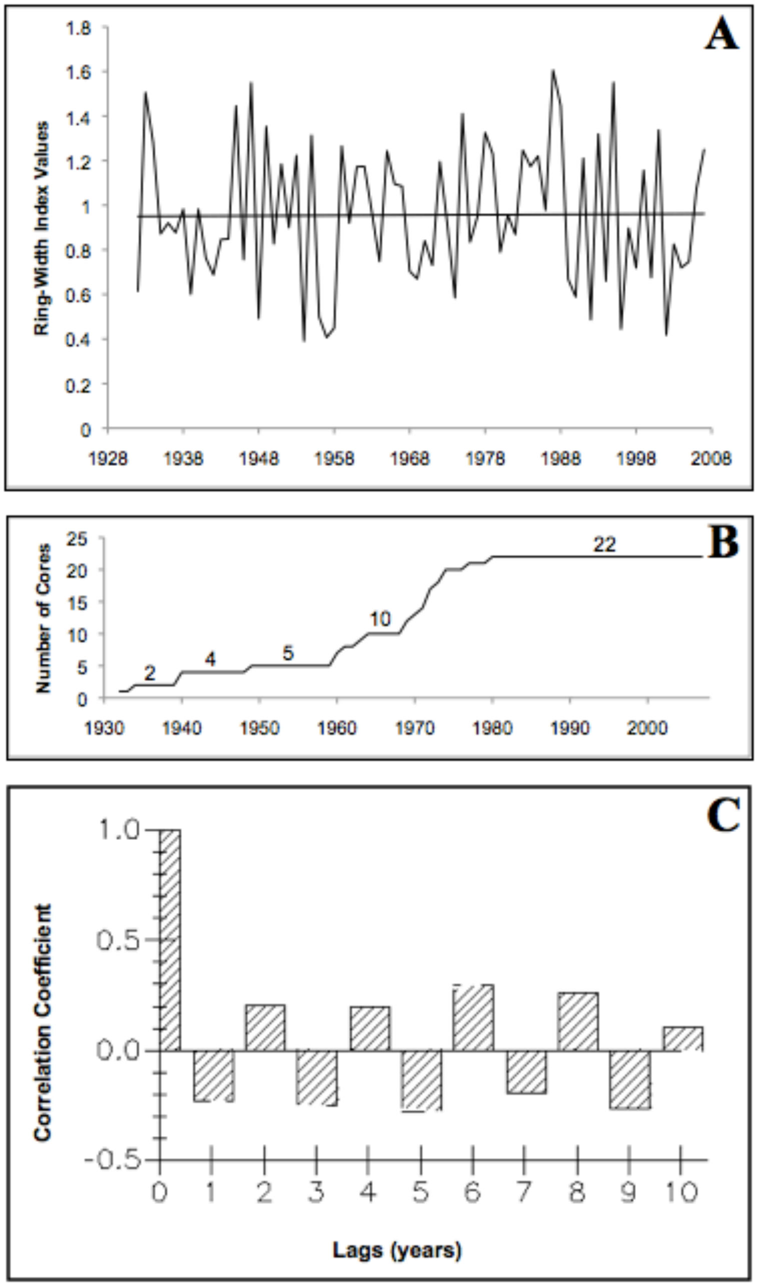


Figure A6. Sopori [A] standard chronology, [B] number and distribution of cores within the standard chronology, and [C] autocorrelation coefficients with a lag of ten years.

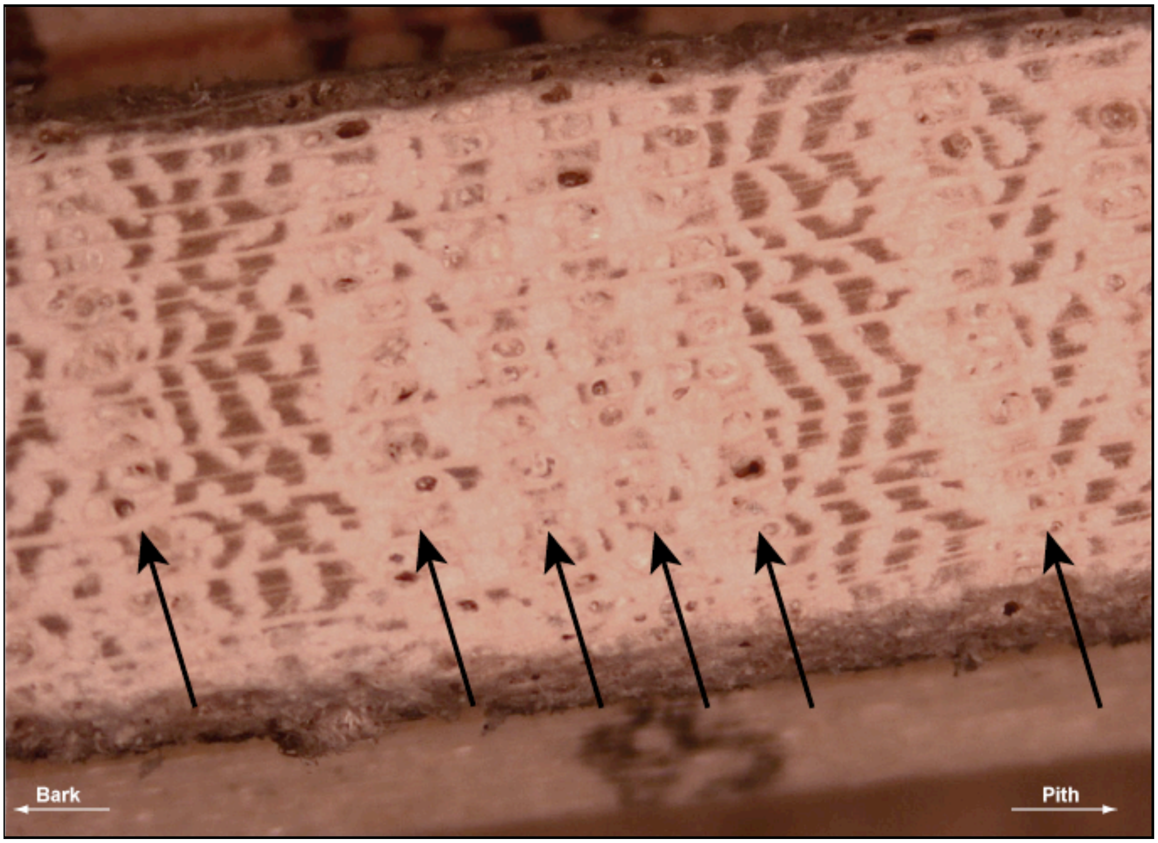


Figure A7. Photo of a *Celtis laevigata* var. *reticulata* increment core. Black arrows point to bands of earlywood.

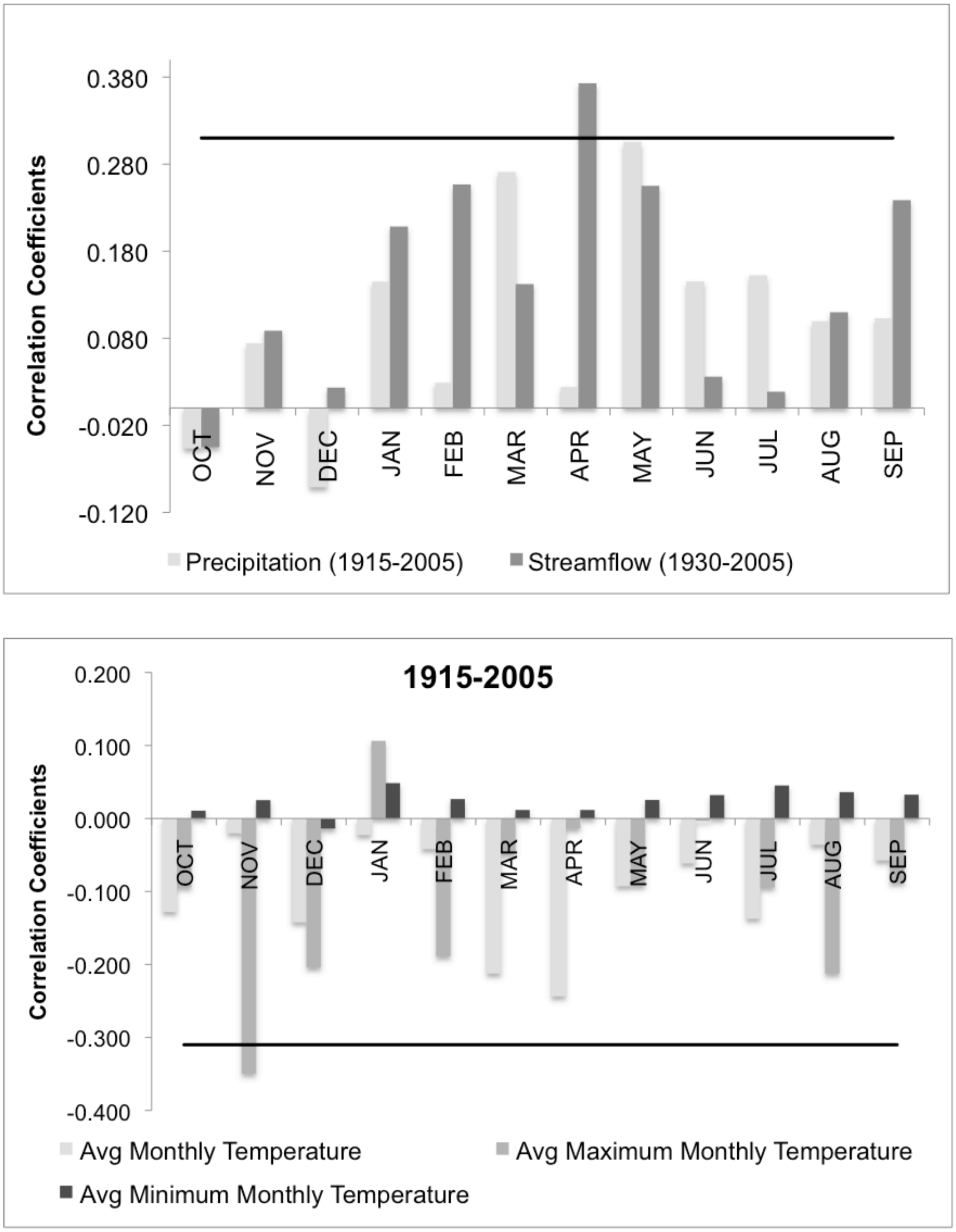


Figure A8. Correlation coefficients for the Buena Vista chronology indices and climate variables as recorded at Nogales. Black lines indicate significance at the 0.01 α level.

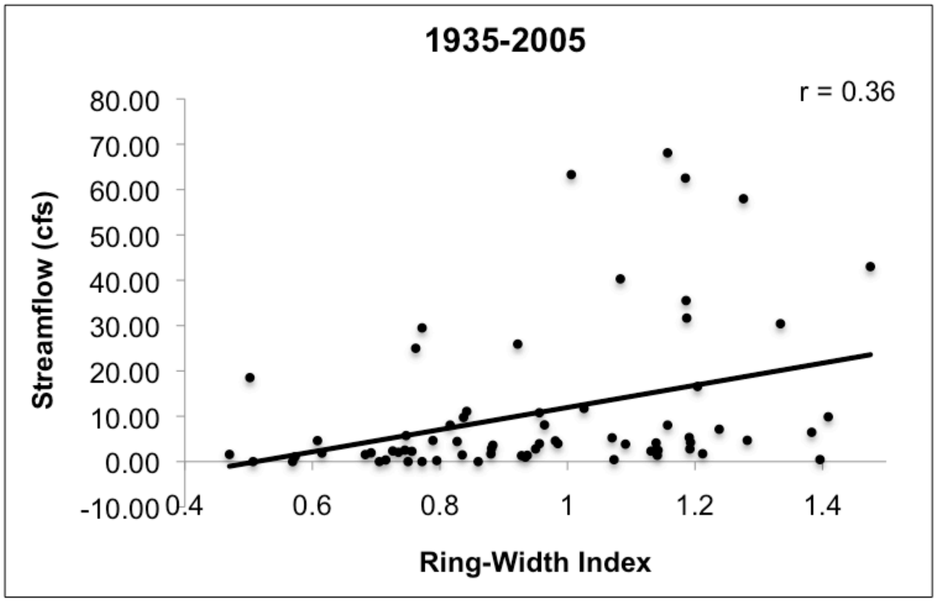


Figure A9. Correlation between ring-width growth and April-June streamflow at Buena Vista.

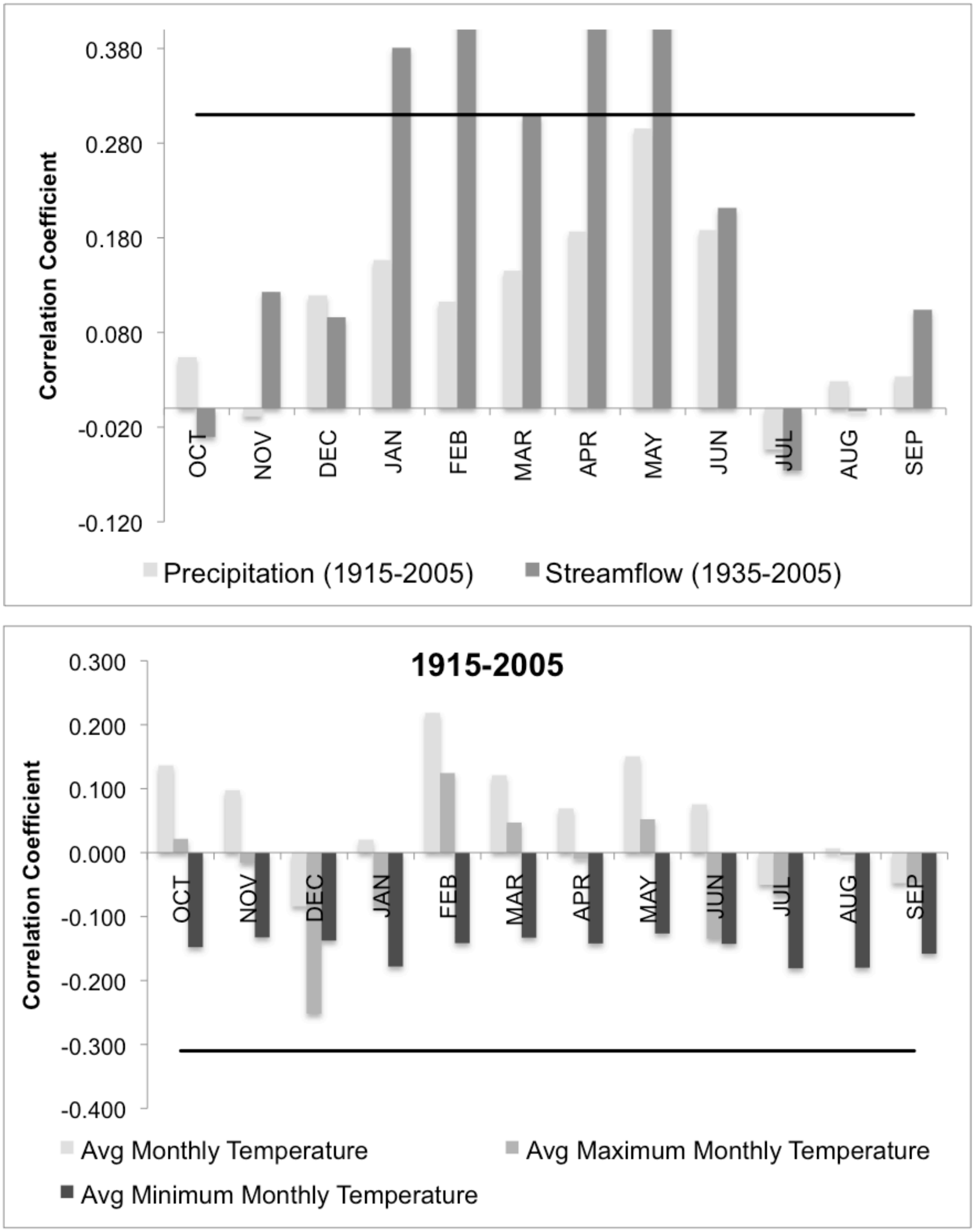


Figure A10. Correlation coefficients for the Calabasas chronology indices and climate variables as recorded at Nogales. Black lines indicate significance at the 0.01 α level.

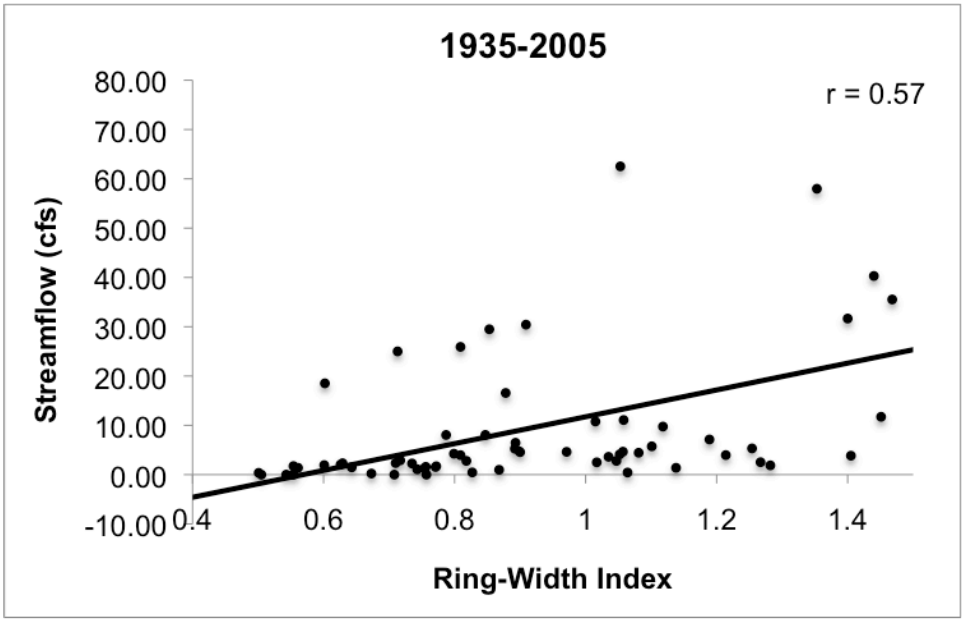


Figure A11. Correlation between ring-width growth and April-June streamflow at Calabasas.

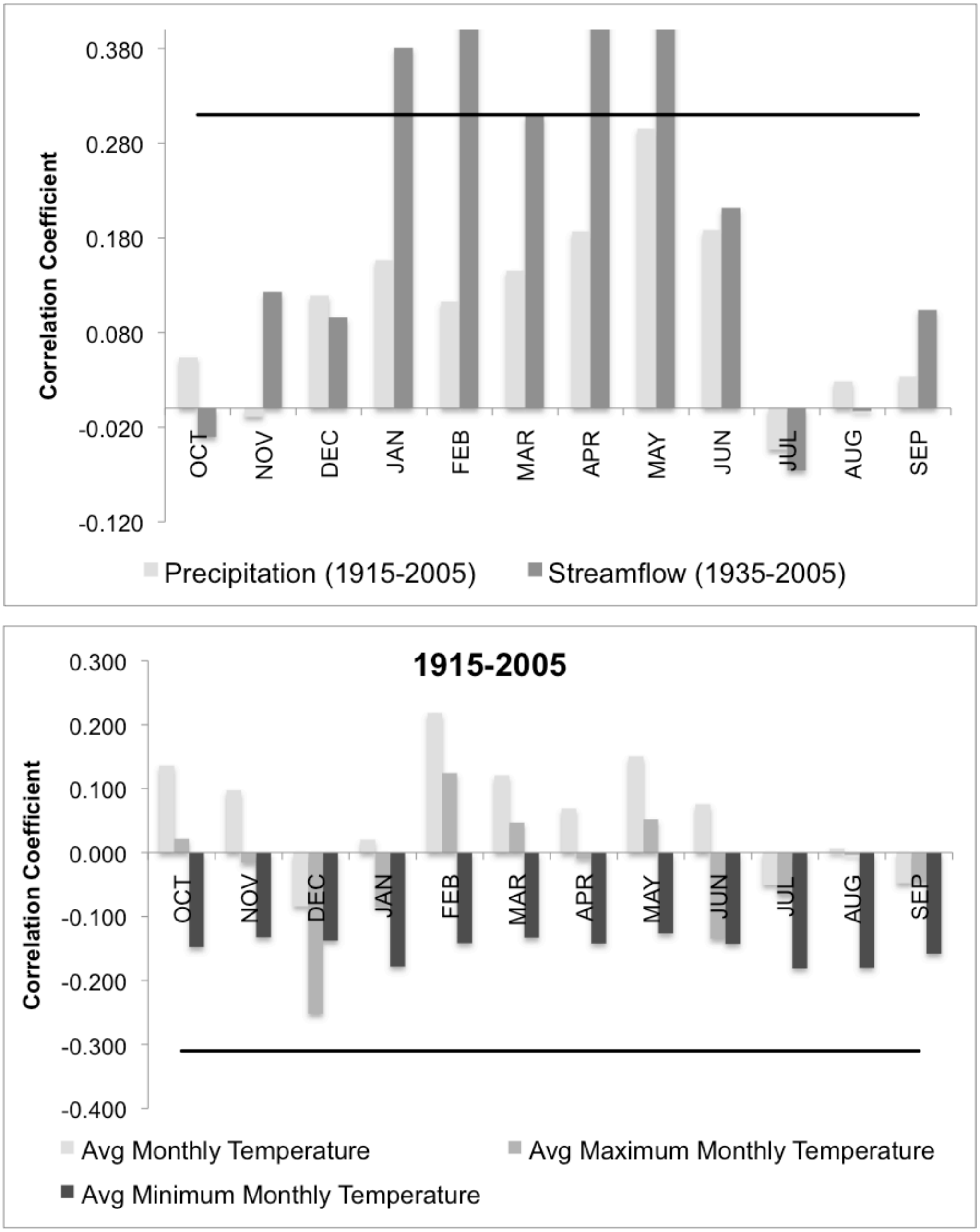
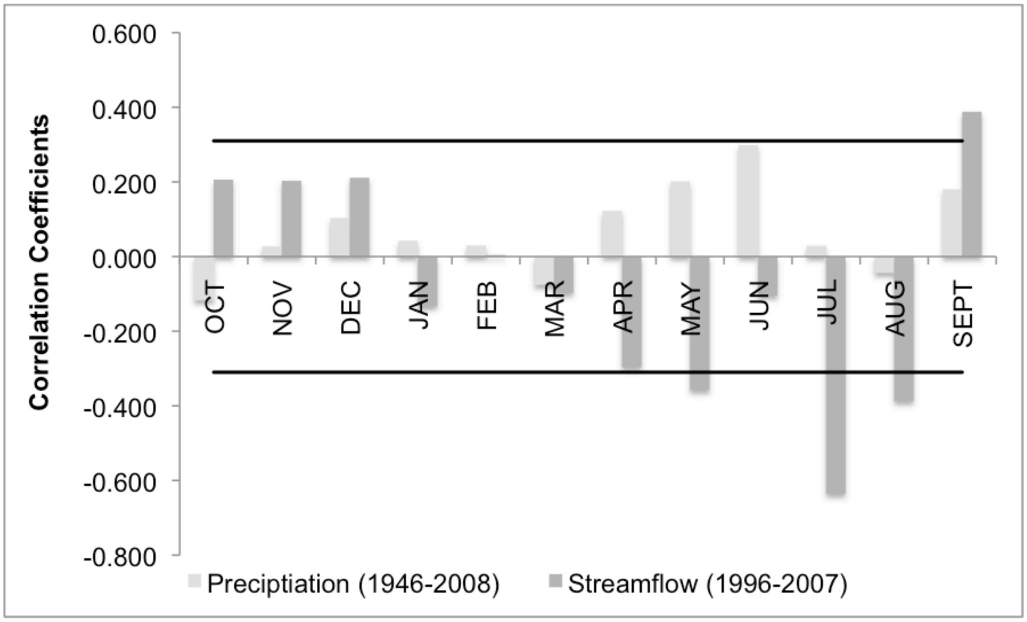


Figure A12. Correlation coefficients for the Sonoita Creek chronology indices and climate variables as recorded at Nogales. Streamflow data is unavailable for this site. Black lines indicate significance at the 0.01 α level.



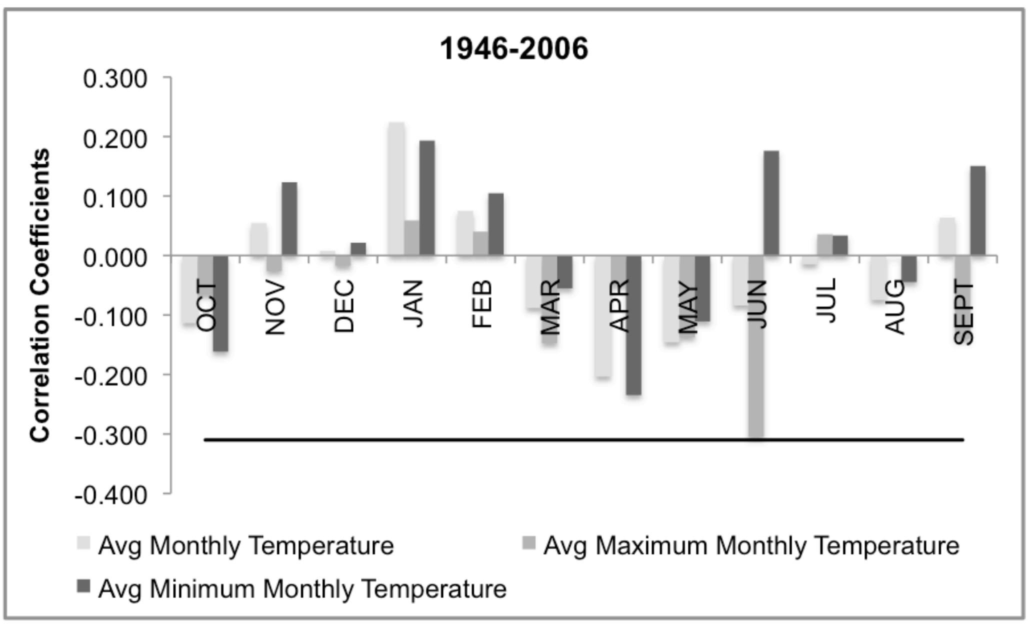


Figure A13. Correlation coefficients for the Tumacácori chronology indices and climate variables. Temperature and precipitation were recorded at Tumacácori. Streamflow was recorded at the USGS Tubac gage for the years 1996-2007. Black lines indicate significance at the 0.01 α level.

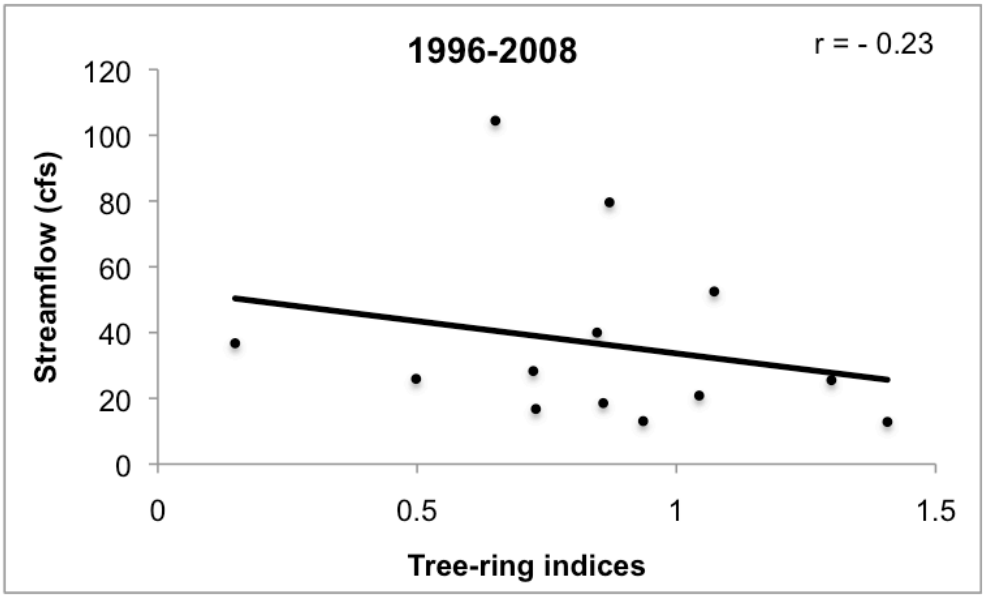


Figure A14. Correlation between ring-width growth and April-June streamflow at Tumacácori.

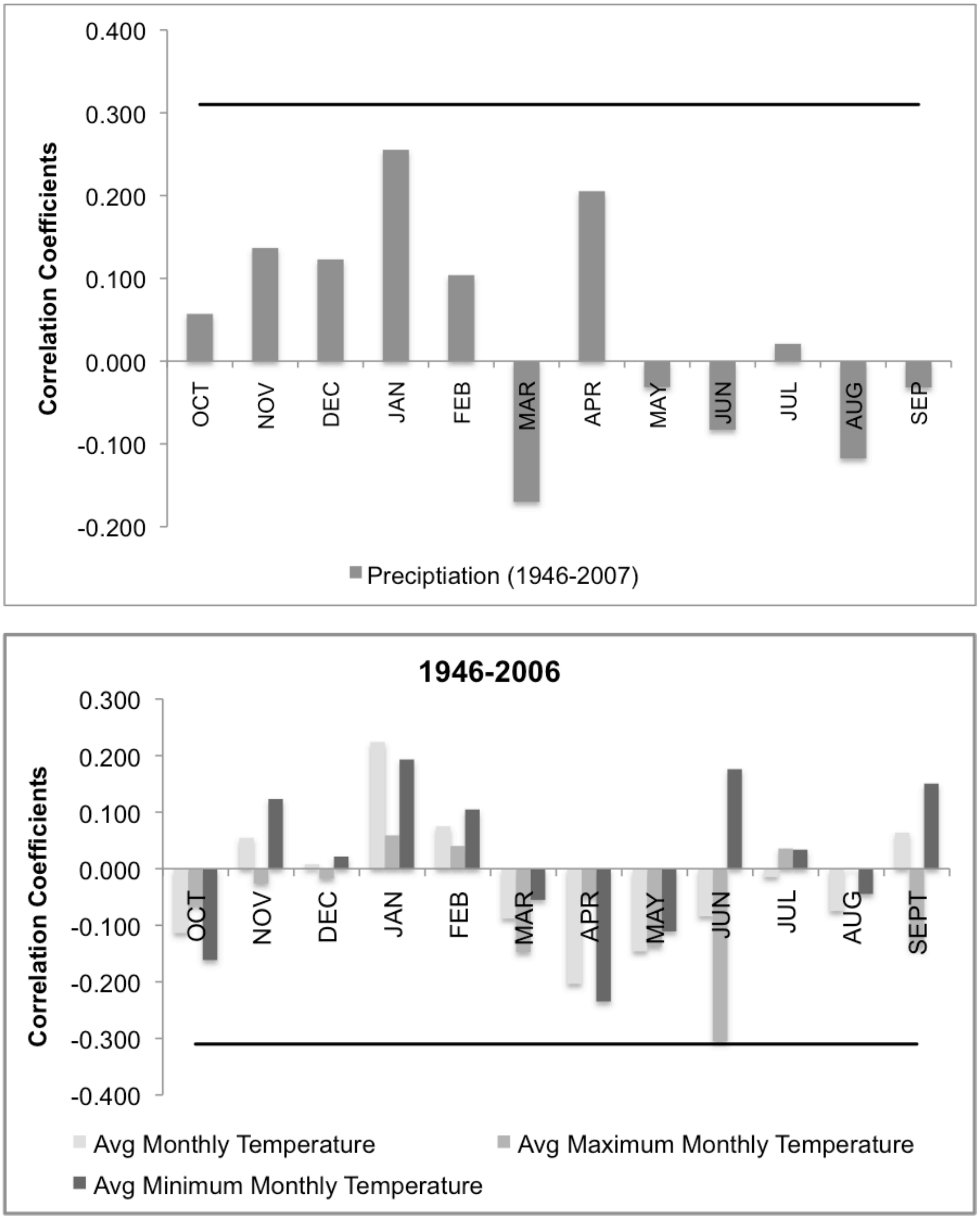


Figure A15. Correlation coefficients for the Sopori chronology indices and climate variables. Temperature and precipitation were recorded at Tumacácori. Streamflow data is unavailable for this site. Black lines indicate significance at the 0.01 α level.

Table A1. Site descriptions for *Celtis laevigata* var. *reticulata* sampling locations in the Upper Santa Cruz River Watershed.

Buena Vista	
Site Description	Trees were sampled within natural riparian habitat adjacent to a private ranch near the Mexican border along the USCR. Sampled trees were evenly distributed between the flat floodplain and slope leading up to xeric oak dominated mesas.
Streamflow	Historically the river maintained perennial flow, however groundwater pumping on either side of the international border has reduced flows since 1996. Today the river is intermittent at this site.
Elevation	1134 m
Vegetation Status	Narrow band of cottonwood/willow vegetation immediately bordering the stream. Cottonwoods are large and have been anecdotally aged at between 75-100 years. Very few younger cottonwoods. Mesquite/hackberry vegetation shows more age and size variation and most of the trees appeared healthy.
Climate Data	3 combined Nogales weather stations
Streamflow Data	USGS Streamflow Gage: 09480500 at Nogales

Calabasas County Park (Guevavi)	
Site Description	Trees were sampled within unirrigated park grounds at the Calabasas County Park and within natural riparian floodplain habitat adjacent to the park.
Streamflow	Historically the river flowed perennially, however the City of Nogales started pumping the groundwater tables in the late 1990s which caused the stream to cease flowing. Today the river only flows during substantial precipitation events.
Elevation	1070 m
Vegetation Status	Very little cottonwood/willow habitat. The hackberry/mesquite forest exhibits substantial signs of drought stress including branch die-back and thin canopies.
Climate Data	3 combined Nogales weather stations
Streamflow Data	USGS Streamflow Gage: 09480500 at Nogales

Table A1 (cont). Site descriptions for *Celtis laevigata* var. *reticulata* sampling locations in the Upper Santa Cruz River Watershed.

Sonoita Creek State Natural Area	
Site Description	Trees were predominantly sampled from a wide and relatively flat berm elevated above Sonoita Creek. Several trees were also sampled along a steep slope leading up from the berm to the surrounding mesas.
Streamflow	Sonoita Creek is a main tributary to the Santa Cruz river and maintained perennial flow until the 1960s when a dam was built to create Lake Patagonia. Today, the river is supported by regular releases from Lake Patagonia, as well as from precipitation events and surface run-off from tributaries to the creek. Flows in the creek diminish several miles before the confluence with the USCR and only reach the USCR in flood events.
Elevation	1176 m
Vegetation Status	There is a healthy cottonwood/willow and mesquite/hackberry habitat present, both displaying age and size distribution. Additional riparian species are abundantly present, including Arizona Walnut (*Juglans major*) and Arizona Sycamore (*Platanus wrightii*).
Climate Data	3 combined Nogales weather stations
Streamflow Data	Streamflow data is unavailable for Sonoita Creek

Tumacácori National Historical Park	
Site Description	Trees were sampled within natural riparian habitat that has reclaimed abandoned agricultural fields.
Streamflow	Streamflow is perennial and comprised mainly of effluent from the NIWTP. During precipitation events, the stream receives flows from Sonoita Creek and Nogales Wash, as well as groundwater discharge.
Elevation	1015 m
Vegetation Status	The park contains dense, mature, and structurally diverse riparian habitat. Additional riparian tree species are abundantly present, including Velvet Ash (*Fraxinus velutina*), Arizona Walnut (*Juglans major*) and Arizona Sycamore (*Platanus wrightii*).
Climate Data	Tumacácori temperature and precipitation data
Streamflow Data	USGS Streamflow Gage 094781740 at Tubac

Table A1 (cont.). Site descriptions for *Celtis laevigata* var. *reticulata* sampling locations in the Upper Santa Cruz River Watershed.

Sopori Wash	
Site Description	Trees were sampled within a wide and terraced mesquite/hackberry forest adjacent to Sopori Wash.
Streamflow	Sopori Wash is ephemeral, flowing only during precipitation events.
Elevation	987 m
Vegetation Status	Scattered large cottonwoods line the edge of Sopori Wash, though the cottonwood/willow habitat is sparse. The mesquite/hackberry forest contains numerous young trees and age and size diversity appears consistent throughout the forest. Several well-delineated terraces run parallel to the Wash, and the mesquite/hackberry habitat is found on the lower terraces.
Climate Data	Tumacácori temperature and precipitation data
Streamflow Data	Streamflow data is unavailable for Sopori Wash

Table A2. Chronology statistics for *Celtis laevigata* var. *reticulata* at each of the five Upper Santa Cruz River sampling locations.

	Buena Vista	**Calabasas County Park**	**Sonoita Creek**	**Tumacácori National Historical Park**	**Sopori Wash**
General Information					
Number of series	20	17	48	30	22
Number of trees	10	8	24	17	11
Number of years	94	101	104	89	76
Calendar dates	1915-2008	1908-2008	1904-2007	1920-2008	1932-2007
COFECHA* Statistics					
Mean series intercorrelation	0.616	0.471	0.569	0.703	0.544
Mean sensitivity	0.399	0.448	0.412	0.398	0.529
Autocorrelation	0.422	0.350	0.434	0.447	0.438
ARSTAN** Standard Chronology					
Standard deviation	0.2567	0.3820	0.2538	0.4019	0.3144
Variance due to autoregression	1.1%	8.2%	1.6%	0.0%	14.5%
ARSTAN Common Interval Analysis					
Common interval analysis period	1966-2008	1952-2007	1950-2007	1978-2007	1977-2007
Mean Correlations					
Among all radii	0.306	0.405	0.356	0.589	0.304
Between trees	0.273	0.000	0.344	0.577	0.200
Within trees	0.762	0.405	0.670	0.805	0.697

* Holmes 1983, Grissino-Mayer 2001
** Cook 1985

APPENDIX B -- RIPARIAN DENDROCHEMISTRY: DETECTING ANTHROPOGENIC GADOLINIUM IN TREES ALONG AN EFFLUENT-DOMINATED RIVER

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B.1 Abstract

This research documents spatial and temporal patterns of effluent uptake by riparian trees through development of a new application for dendrochronology, specifically dendrochemistry. The rare-earth element gadolinium (Gd), is a known micropollutant in its anthropogenic form that was first used in select medical procedures in 1988 and subsequently discharged via treatment plants into waterways. Riparian trees that utilize effluent-dominated surface water uptake Gd where it remains in annual growth rings. Because anthropogenic Gd was introduced into waterways after 1988, there is a clear presence/absence date stamp that makes Gd an ideal marker for a dendrochronological study. Results from the Upper Santa Cruz River in southeastern Arizona show elevated levels of Gd in effluent-dominated surface flows, confirming that anthropogenic Gd is present. Gd was found in the growth rings of cottonwood trees (*Populus fremontii*) that are growing in the floodway adjacent to the effluent-dominated portion of the stream. The presence of Gd in cottonwood annual rings confirms that the trees are utilizing effluent. Temporal patterns of Gd concentrations in trees directly adjacent to the stream may be reflective of high-frequency changes in surface water quality. Information provided by the chemical composition of tree rings can be a useful monitoring tool to evaluate the spatial and temporal patterns of effluent use in riparian trees and to identify high-frequency changes in surface water quality.

Keywords: Dendrochemistry, Gadolinium, Rare Earth Elements, Riparian, *Populus fremontii*, Cottonwood Trees, Ecological Monitoring

B.2 Introduction

Functioning riparian ecosystems in the southwestern United States are indicators of the health of river basins and play a pivotal role in maintaining streamflow conditions, facilitating groundwater recharge, providing natural water quality enhancement, and supporting biodiversity (Naiman and Decamps 1997, Naiman et al. 2005, Brauman et al. 2007). In spite of their importance, these systems are under increasing pressure from human alteration to the quality and quantity of surface and groundwater (Postel 2000, Lite and Stromberg 2005). As one mitigation to these threats, municipal wastewater (effluent) can play an important role in ecosystem restoration by providing instream flows for vegetation and recharging local water tables (Patten et al. 1998, Bouwer 2002, Brooks et al. 2006). Increasingly, effluent flows may be critical to riparian survival in arid and semi-arid river systems where surface water and groundwater have been de-coupled due to anthropogenic change and drought (Patten et al. 1998).

While there are many benefits to utilizing effluent for the maintenance of instream flows, there are numerous unresolved ecohydrological issues regarding the release of effluent into ground-water dependent riparian systems. Few if any studies have quantified the full suite of benefits and impacts to ecosystem function in effluent-dominated streams. There is little knowledge about how native riparian vegetation incorporates and responds to continued inflows of nutrient-rich effluent. The need to address this knowledge gap is particularly compelling within the context of climate variability and the potential for prolonged drought and rising temperatures to increase freshwater demands, further degrade riparian systems, and potentially increase the number of streams reliant upon effluent to maintain surface flows and associated riparian habitats. Ultimately, a lack of understanding about the dynamics of effluent-dominated streams has created a void in methods suitable for evaluating the ecological integrity of these systems (Brooks et al. 2006).

To address knowledge gaps in effluent-dominated riparian systems, this research documents spatial and temporal patterns of effluent uptake by riparian trees through development of an innovative application of dendrochronology, specifically dendrochemistry. Dendrochemistry is defined as the measurement and interpretation of the concentration of elements in tree rings (Amato 1988). Dendrochemical measurements can be utilized to estimate relative temporal changes in the availability of elements in the surrounding air, water, or soil utilized by trees (Lewis 1995).

Dendrochemistry has multiple applications for investigating temporal and spatial variability of elements in the environment. While trees do interact with their environment both chemically and physically (Smith and Shortle 1996), dendrochemistry can be an effective tool for reconstructing environmental change (Watmough 1999). Numerous studies have focused on heavy metal concentrations in tree rings (Lepp 1975) as a method to determine the timing and geographic distribution of metals including mercury (Abreu et al. 2008), lead (Hagemeyer and Weinand 1996, Watmough et al. 1999, Bindler et al. 2004), and tungsten (Sheppard et al. 2007). Dendrochemistry has been successfully applied to investigations into groundwater contamination (Vroblesky and Yanosky 1990, Yanosky et al. 2001), and a related branch of dendrochemistry has focused on examining mechanisms of essential plant nutrition, including uptake patterns of nitrogen (Poulson et al. 1995) and forest nutrition (Hutchinson et al. 1998, Watmough et al. 1998).

Dendrochemistry is an evolving field of research and numerous elements remain unexamined as tracers of environmental contamination. No studies have yet investigated the utility of rare earth element (REE) signatures in tree rings for tracing historic changes in groundwater and surface water quality. The REE gadolinium (Gd) is a known micropollutant that enters streams from wastewater treatment plants and has been identified as a tracer for effluent movement in streams and groundwater (Bau et al. 2006). Gd was first used in select medical procedures in 1988 and subsequently discharged via treatment plants into waterways (Bau and Dulski 1996). In effluent-dominated rivers that support functioning riparian forests, trees can display a temporal Gd presence/absence date stamp (before and after 1988) in annual tree rings, thereby making Gd an ideal marker for analyzing effluent-related changes in groundwater and surface water quality in riparian environments.

This research investigates the interaction of effluent with riparian vegetation by addressing four questions:

1. Is gadolinium (Gd) present in effluent-dominated surface and groundwater?
2. Do Fremont cottonwood (*Populus fremontii*) trees along the effluent-dominated stream contain Gd in their growth rings?
3. Do Gd concentrations vary temporally in cottonwood annual rings?
4. Can temporal and spatial variability of Gd concentrations be correlated with ecohydrologic characteristics of the stream, such as clogging layer dynamics?

B.2.1 Rare earth elements

Rare earth elements (REEs) are part of the lanthanide series in the periodic table, and each element shares nearly identical chemical and physical properties. REEs display a systematic decrease in ionic radius as their atomic number increases, a pattern referred to as “lanthanide contraction” (Johannesson 2005, Stille et al. 2006a). This behavior results in coherent behavior in the entire lanthanide series (La-Lu) (Johannesson et al. 1997). Despite this coherence, there is evidence that heavy REEs (Dy-Lu) and light REEs (La-Sm) can behave differently during certain chemical processes such as adsorption and complexation (Stille et al. 2006b).

The most stable oxidation state of REEs in natural waters is trivalent (Stille et al. 2006a). Because of this, REEs can adsorb strongly on surfaces of rocks or bind to organic substances such as humic acid (Ozaki and Enomoto 2001). As evidence of this condition, suspended material in rivers reflects basin geology (Goldstein and Jacobsen 1988) and groundwater typically displays an REE signature reflective of the rocks through which the water has flowed or the basin material in which the groundwater resides (Johannesson et al. 1999, Johannesson et al. 2000). REE patterns are therefore regionally specific.

Little is known about the relationship between REEs and vegetation. Due to their tendency to adsorb to rock surfaces, REEs are minimally available to plants through soil. However, plants exhibit preferential light REE uptake patterns at the root-water-soil interface along streams and rivers (Stille et al. 2006a). In addition, some fern species are known REE accumulator plants (Ozaki and Enomoto 2001). Considering that studies have shown REEs to be instructive geochemical tracers of the origins of suspended and dissolved sediments in rivers (Goldstein and Jacobsen 1987, Goldstein and Jacobsen 1988, Stille et al. 2003), investigating REE uptake patterns in vegetation, and specifically in annual tree rings of riparian plant species, may offer insights into changes in river chemistry.

B.2.2 Anthropogenic gadolinium

Notable among the REEs, gadolinium (Gd) can be found in both natural and anthropogenic forms and can serve as an indicator of changing water quality. Anthropogenic Gd (Gd_{ANTHRO}) enrichment results from the use of gadopentetic acid (Gd-DTPA) as a contrasting agent for MRIs (Verplanck et al. 2005). Gd_{ANTHRO} organic compounds were first used in the United States in 1988 as contrasting agents in MRIs. Patients undergoing MRI procedures take Gd-DTPA either orally or intravenously and excrete the substance unaltered. Gd_{ANTHRO} is very stable for over 6 months under natural conditions, is highly water soluble and mobile in surface and groundwater systems, and does not adsorb onto surrounding materials, as do natural REEs (Knappe et al. 2005, Bau et al. 2006).

Increased concentrations of Gd_{ANTHRO} in river systems that receive treated municipal effluent were reported in 1996 (Bau and Dulski 1996). During the past decade, elevated levels of Gd_{ANTHRO} in rivers, lakes, and groundwater have been documented in Europe (Bau and Dulski 1996b, Elbaz-Poulichet et al. 2002, Moller et al. 2002, Knappe et al. 2005, Kulaksiz and Bau 2007), Japan (Ogata and Terakado 2006), and North America (Verplanck et al. 2005, Bau et al. 2006). Gd_{ANTHRO} has the potential to serve as a tracer for monitoring the pathways and presence of municipal effluent in waterways and drinking water (Bau et al. 2006).

Numerous questions remain about Gd_{ANTHRO} and must be investigated before Gd_{ANTHRO} can be effectively used as a tracer or for monitoring protocols. While research has focused on concentrations of Gd_{ANTHRO} in sources of water, more detailed research is required to understand processes that control the fate and transport of Gd_{ANTHRO} (Verplanck et al. 2005). In particular, Gd_{ANTHRO} uptake patterns in riparian vegetation have not yet been investigated. Relative amounts of Gd_{ANTHRO} within annual growth rings could provide a historical picture of Gd_{ANTHRO} uptake patterns in trees over time. Addressing this knowledge gap surrounding the connection between Gd_{ANTHRO} and riparian vegetation, this study documents spatial patterns of effluent uptake by *Populus fremontii* along an arid, effluent-dominated river through a new application of dendrochemistry.

B.3 Materials and Methods

B.3.1 Study Area

The Upper Santa Cruz River (USCR) is a bi-national river that flows through the rapidly growing urban area that encompasses Nogales, Sonora (Mexico) and Nogales, Arizona. The Upper Santa Cruz River relies upon three contributing water sources: surface runoff, effluent from the Nogales International Wastewater Treatment Plant (NIWTP), and groundwater discharge.

The river is characterized by a series of shallow and undulating micro-basins that together form the underlying floodplain aquifer. Groundwater can be found in three relatively distinct aquifers. The most accessible aquifer, referred to as the Younger Alluvium, fills a series of seven independent sub-basins immediately bordering and underlying the stream channel (Figure 1). The Younger Alluvium basins are primarily comprised of gravel, sand, and clay of Pliocene and Pleistocene age (Nelson 2007). Groundwater levels in the USCR basin have varied over time in response to climate conditions and human use patterns. Due to the shallowness of the aquifer and the permeable nature of the alluvium, the water table is sensitive to climatic changes, rising quickly during heavy precipitation and depleting rapidly during drought. Recharge from the stream into groundwater tables is tightly linked to precipitation patterns. The year 2000 was a flood-dominated year with 61,674,092 cubic meters (50,000 acre-feet (af)) recharge, while 2002 was the start of a drought and there was less than 24,669,636 cubic meters (20,000 af) of recharge (Nelson 2007). Surface flow in the river is ephemeral and intermittent from the headwaters, through Sonora, and into Arizona for about 16 km.

At the confluence of Sonoita Creek and the USCR, a perennial reach of the river runs north for about 48 km as a result of daily effluent discharges from the Nogales International Wastewater Treatment Plant (NIWTP). The NIWTP began operation in the 1950’s and reached its current discharge rate after a significant upgrade in 1992. Historic agricultural operations cleared cottonwood and mesquite forests for fields up until the 1930s (Webb et al. 2007). However, the daily inflows of effluent from the NIWTP have revived the riparian ecosystem, and almost 600 species of vertebrates and invertebrates now depend upon the river system for either temporary or permanent habitat (Powell 2004). The Arizona Department of Water Resources reports that since effluent subsidies began in 1972, the discharge of treated effluent into the channel resulted in an approximately 0.8 meter average increase in local groundwater tables (Corkhill and Dubas 2007). A corresponding analysis of riparian vegetation patterns over time suggests that riparian vegetation has increased in density and extent due to the introduction of effluent into the USCR system. Recent synthesis of historic arial photographs and current satellite imagery shows that floodplain lands receiving direct effluent subsidies have experienced a rapid increase of mature riparian forests from 1984 - 2004 (Villarreal 2009).

Effluent discharged into the Upper Santa Cruz River can either enhance or hinder riparian vegetation growth, depending on water quality and hydrologic conditions. Effluent is known to be high in nitrogen, which can benefit riparian vegetation by stimulating growth (Patten et al. 1998, Marler et al. 2001). On the other hand, nitrogen also fosters algae growth that can form thick mats on the bottom of the stream channel and lead to clogging of surface sediments (Boulton et al. 1998, Hancock 2002). In the absence of seasonal floods, the algal mats, also known as clogging layers, can seal the bottom of the stream channel, decreasing infiltration and recharge and hindering the connection between surface water, subflow, and groundwater (Brunke and Gonser 1997). The clogging layer can retain flows in the stream channel while the groundwater tables drop below the root zone of riparian plants. Paradoxically, riparian trees can then suffer from drought conditions even while there is water in the stream.

B.3.2 Field sampling

Collections of Fremont cottonwood (*Populus fremontii*) were made from living trees within the 100-year floodplain in the Upper Santa Cruz River (USCR) watershed (Figure 1) to utilize for dendrochemical analysis. Increment core samples of radial growth were collected from suitable, mature, and healthy cottonwood trees using a 5.15-mm diameter Haglof borer (Forestry Suppliers, Inc, Jackson, MS). Increment borers were cleaned with isopropyl alcohol after each sample was taken to minimize contamination between trees. Two samples were taken from each tree, one approximately five inches above the other for replication purposes. Three distinct sites within the USCR watershed were selected for sampling (Figure 1).

1. Effluent Site - Six trees were sampled along the effluent-dominated portion of the USCR through Tumacácori National Historical Park. Three trees were sampled immediately adjacent to the effluent-dominated stream. Three trees were sampled ~200 meters from the stream and within a band of mature cottonwoods that most likely germinated shortly after notable flood events in 1977, 1983, and 1993 (Webb et al. 2007).

2. Control Site (main stem of the river) - Eight trees were sampled at two adjacent ranches immediately north of the U.S.-Mexico border and immediately overlaying the Buena Vista groundwater basin (Figure 1). This site is about 16 km south (upstream) of the NIWTP and therefore does not receive effluent subsidies. Two collections of trees were made at the northern and southern ends of the basin. The southern end of the basin includes a small spring that supports year-round water for about three kilometers in the channel.

3. Control Site (tributary) - Control samples were gathered from trees along Fresno Canyon, a tertiary tributary to the USCR in Sonoita Creek State Natural Area. Fresno Creek is ephemeral and only flows during rainfall events.

Surface water samples were taken to ascertain whether Gd was present in surface flows and/or in the groundwater both upstream and downstream of the effluent discharge point. Samples were collected at publicly accessible points along the river, both north and south of the Nogales International Wastewater Treatment Plant (NIWTP), including the spring located above the Buena Vista groundwater basin at the main stem control site. Two sets of surface water samples were taken before and after the summer monsoon rainy season (July-September) with the aim of keeping the dilution of the Gd_{ANTHRO} signal by precipitation runoff events to a minimum. Groundwater was collected from wells near surface water sampling locations. Soil samples were collected within 30 m of the streambed at Tumacácori NHP and at the main stem control site. All samples were taken from 0.5 m depth within the floodplain soil. Surface dust samples were taken in three clusters downstream and upstream of the NIWTP to assess airborne transport of anthropogenic Gd (Fergusson and Ryan 1984, Thornton et al. 1985).

B.3.3 Sample preparation

Increment core samples were prepared following standard dendrochronological techniques (Phipps 1985). Each sample was finely sanded to provide clearly polished transverse views of annual growth rings. Cottonwood trees are difficult to precisely crossdate due to variable patterns of complacent and false rings (Willms et al. 2006). However, samples were visually inspected under a microscope and confidently assigned approximate dates by counting rings back in time from the bark and matching patterns of narrow and wide rings (Douglass 1941). Each core includes or pre-dates 1988, the first year that Gd_{ANTHRO} was used in MRI procedures and thus introduced into effluent-dominated streams via water treatment plants. Cores were cut into 2- to 3-year increments for analysis. The wood, soil, and dust samples were chemically digested and analyzed by inductively coupled plasma mass spectroscopy (ICP-MS) at the UA Soil, Water, and Environmental Sciences Arizona Laboratory of Emerging Contaminants (ALEC). Surface and groundwater samples were also measured by ICP-MS at the ALEC and were analyzed for major ions and REE concentrations.

B.3.4 Data analysis

To determine the pattern of REE concentrations in all samples (surface water, groundwater, trees, dust, and soil), values of raw concentrations were normalized to the North American Shale Composite (Gromet et al. 1984). REEs are subject to the Oddo-Harkins effect, which suggests that during the evolution of the solar system, even-atomic-number elements were more stable than neighboring odd-number elements (Verplanck et al. 2005). For example, Gd (atomic number 64) is naturally enriched compared to its nearest neighbors Eu (atomic number 63) and Tb (atomic number 65). Normalizing to North American Shale Composite removes this effect.

Once normalized, known anomalies may still occur. As a general rule, REEs are trivalent; however, cerium (Ce) and europium (Eu) are redox-sensitive and may occur as tetra- and di-valent cations, thus behaving anomalously from other REEs (Kulaksiz and Bau 2007). In addition, vegetation preferentially accumulates Eu (Stille et al. 2006). Owing to this documented anomalous behavior, standardized Eu was not included in this analysis.

Elevated levels of Gd in surface water and groundwater is expressed by the geogenic ratio of the standardized measured values of Gd (Gd_{SN}) and the interpolated abundance of Gd (Gd^*_{SN}) (Knappe et al. 2005, Bau et al. 2006).

$$Gd_{SN}/Gd^*_{SN} = Gd_{SN} / (0.33Sm_{SN} + 0.67Tb_{SN}) \quad (1)$$

Eq (1) is derived from the predictable cohesion among REEs by interpolating the expected natural abundances of shale-normalized Gd in water samples from Gd's nearest stable neighbors Samarium (Sm) and Terbium (Tb).

Gd_{SN} concentrations can vary among sites depending upon complexation patterns across the 15-member series of REEs. Two distinct patterns of complexation behavior exist between the light REEs (La-Eu) and heavy REEs (Tb-Lu), and Gd can alternately behave as a heavy REE for weak complexation or as a light REE for strong complexation (Byrne and Li 1995). To accommodate this variability, a geogenic ratio of 1.3 is defined as the threshold that distinguishes an anthropogenic anomaly from natural Gd_{SN} abundance in freshwater (Moller et al. 2002, Knappe et al. 2005).

The geogenic ratio was calculated for surface water samples pre- and post-monsoon, as well as for groundwater samples. Geogenic ratios were not calculated for tree samples for two primary reasons. First, concentrations of elements found in wood samples are mediated by the exposure of the roots to the elements, selective uptake mechanisms, and the degree of utilization within the tree (Balouet et al. 2007). Second, absolute concentrations of Gd_{SN} in the trees are extremely small (nanograms/gram). If the input of anthropogenic Gd is small in water samples, the geogenic fraction can be erroneous

(Knappe et al. 2005). Therefore, to avoid erroneous results brought on by using the ratio analysis for the trees, Gd_{SN} trends are compared against standardized trends for all REEs.

B.4 Results

B.4.1 Gd_{SN} in water, soil, and dust samples

Geogenic ratio results from surface water samples show a clear delineation between samples upstream and downstream of the NIWTP. All samples taken from upstream of the NIWTP fall between 0.3 and 1.0, which is below the 1.3 anthropogenic threshold (Figure 2). All of the effluent-dominated surface water samples taken from downstream of the NIWTP are between 1.5 and 4.0. These values are well above the 1.3 anthropogenic threshold. All of the groundwater samples from both upstream and downstream of the NIWTP fall between 0.5 and 1.0, below the 1.3 anthropogenic threshold.

For dust and soil samples, standardized values of Gd were analyzed in comparison with other REEs. Values for Gd_{SN} were negligible, just above zero (Figure 3).

B.4.2 Gd_{SN} in *Populus fremontii* trees

Under natural conditions, all REE elements (with the exception of Eu) display coherent behavior, due mainly to their similar physiologic properties (Bau and Dulski 1996). In the cottonwood trees sampled adjacent to the effluent-dominated river, this tight coherence is evident for all of the standardized REE values except for Gd_{SN}. Distinct from other standardized REEs, Gd_{SN} is elevated by as much as a factor of two (Figure 4). Furthermore, a common temporal pattern is evident in the three trees sampled directly adjacent to the effluent-dominated stream. Each of the three trees includes a spike in Gd_{SN} concentrations around the year 2005. The temporal pattern is not uniform for the three trees located 200 meters from the stream channel. Only one of these trees exhibits a spike in 2005, while the other two trees show a reduction in relative Gd_{SN} concentrations in 2005.

Trees located in the northern portion of the control site also showed elevated levels of Gd_{SN} relative to other REEs (Figure 5). In contrast, trees located in the southern portion of the control site did not demonstrate elevated levels of Gd_{SN}. Trees sampled at the tributary control site did not display elevated levels of Gd_{SN} (Figure 5).

B.5 Discussion

B.5.1 Anthropogenic Gd in surface and groundwater

Results from surface water samples collected at control sites upstream of the NIWTP indicate that anthropogenic Gd (Gd_{ANTHRO}) is absent in natural stream flows that do not contain treated effluent. However, effluent-dominated surface water flows downstream of the treatment plant do contain elevated levels of Gd_{SN} relative to other REEs and above the anthropogenic threshold. This suggests that Gd_{ANTHRO} is present in effluent-dominated surface water flows and moves downstream through the cottonwood dominated riparian floodplain.

While effluent-dominated surface water samples contain Gd_{ANTHRO}, groundwater tables that underlie the effluent-dominated portion of the stream do not contain detectable amounts of Gd_{ANTHRO}. Considering evidence that effluent is recharging groundwater tables (Scott et al. 1997, Nelson 2007), this is a surprising result. Dilution may account for the absence of detectable Gd_{ANTHRO} levels in groundwater. Effluent that does recharge groundwater tables is subsumed by the volume of water already present in the groundwater tables. If Gd_{ANTHRO} is present in groundwater, it may therefore not be present in detectable amounts. More extensive samples of groundwater at varying depths and distance from the stream would aid in determining the degree of dilution and if Gd_{ANTHRO} values are present at shallower depths or directly underlying the stream.

B.5.2 Detectable levels of Gd_{ANTHRO} in *Populus fremontii* trees

Cottonwood trees growing adjacent to the effluent-dominated stream contain elevated levels of Gd_{SN} relative to other standardized REEs in their annual growth rings. These elevated levels of Gd_{SN} in the annual growth rings, paired with detectable levels of Gd_{ANTHRO} in effluent-dominated surface water samples, suggest that excess Gd_{SN} in cottonwood trees is anthropogenic in origin. Furthermore, the presence of Gd_{ANTHRO} in annual growth rings of cottonwood trees serves an indication that trees are utilizing effluent at some point during their annual growth cycle.

Cottonwood trees along the Upper Santa Cruz River are not long-lived (< 40 years), and many of the trees within the riparian area geminated after two major floods in 1977, 1983, and 1993 (Webb et al. 2007). As a result, only two of the six trees sampled along the effluent-dominated stretch of the river pre-dates 1988, when Gd-DTPA was first used in MRI procedures and discharged into waterways via municipal treatment facilities. Of these two trees, one tree indicates elevated levels of Gd_{ANTHRO} prior to 1988. This result is likely a reflection of the anatomy of cottonwood trees. *Populus* species have numerous rings in the sapwood, the area of the tree involved in the upward conduction of sap (Hoadley 1990, Cutter and Guyette 1993). As a result, concentrations of nutrients and elements taken up by a tree over the course of one growth year can be contained within annual rings of previous years. To accommodate this physiological characteristic of the cottonwood in this study, concentrations of Gd_{ANTHRO} were analyzed in 2- to 3-year blocks so that the general trend of uptake patterns would be reflected.

Interestingly, elevated levels of Gd_{ANTHRO} were also found in trees sampled in the northern part of the control site, 10 miles upstream of the NIWTP effluent discharge point. Trees sampled in the southern portion of the control site did not contain elevated Gd levels, nor did the soil, dust, or surface water samples taken from the perennial spring at this location. There is little concrete evidence to suggest why Gd_{SN} would be elevated relative to other standardized REEs in the northern part of the control site while trees in the southern half of the control site show cohesive levels of all standardized REEs, including Gd_{SN}. However, anecdotal evidence may offer a suggestion as to this difference. The northern part of the control site is located approximately two miles north of the U.S.-Mexico border and three miles east of the twin border cities of Nogales, Sonora (population 500,000) and Nogales, Arizona (population 20,000). The northern portion of the control site is also located downstream of a small tributary that originates in Sonora, Mexico and conveys water from Sonora. It is plausible that geologic faults convey groundwater flow away from Nogales, Sonora towards lower-elevation locations such as the northern portion of the control site (K. Nelson, pers. comm.). Many of the washes and much of the surface runoff in Nogales, Sonora contain flows from leaky or broken sewer pipes (Morehouse et al. 2000). While there is little to no data collection on the volume or chemical composition of these flows, it is conceivable that wastewater from broken sewer pipes could contain elevated levels of Gd_{ANTHRO}. These flows could then contribute to the groundwater that is conveyed to the northern portion of the control site for this study. Under this scenario, Gd_{ANTHRO} could be recorded in annual rings of riparian trees.

B.5.3 Gd_{ANTHRO} Spike in TUMA trees around the year 2005

Cottonwood trees from the effluent-dominated portion of the river display temporal differences in relative Gd_{ANTHRO} values. Gd_{ANTHRO} concentrations were measured in two-year increments at the effluent-dominated site. The temporal pattern and ~2005 spike in Gd_{ANTHRO} in the near stream trees at Tumacácori complements investigations into clogging layer dynamics along the USCR. A University of Arizona study confirmed the existence of a clogging layer in the stream channel of the USCR north of the NIWTP and concluded that two consecutive floods of 350 cfs or more were needed to scour the riverbed and restore the connection between the stream channel and shallow water tables (Treese 2009). In the 1980s and 1990s, above-average precipitation and frequent floods supported gaining stream conditions, which diluted nutrient-rich effluent flows with groundwater to prevent (or at least slow) the formation of the clogging layer. The year 2001 marked the start of a regional drought, and there were few floods in the USCR watershed from 2002 - 2005. Groundwater levels dropped and gaining conditions gave way to losing conditions. Without the mitigating influence of groundwater dilution the clogging layer grew and ultimately severed the groundwater-surface water connection in the hyporheic zone (Treese 2008). In 2005, two consecutive floods above 350 cfs scoured the streambed and removed the clogging layer, thereby restoring the connection between the stream and shallow groundwater tables. A spike in Gd_{ANTHRO} concentrations in the near-stream trees at the effluent-dominated experimental site coincides with the 2005 floods and the break-up of the clogging layer and suggests a general temporal recording of these events in the tree rings.

B.5.4 Gd_{ANTHRO} as tracer for effluent dispersion and utilization

In light of rising demands for freshwater and rapid rates of riparian ecosystem degradation, effluent is becoming an increasingly viable water augmentation option to address escalating competition for water among urban, agricultural, industrial, and environmental demands (Jacobs and Holway 2004, Corwin and Bradford 2008). In particular, effluent can provide consistent flows to rivers and support both restoration and maintenance of riparian vegetation. However, effluent-dominated streams have unique water quality characteristics that distinguish them from natural streams. Numerous questions remain unanswered about the impacts of effluent on riparian function, the degree to which riparian vegetation may be utilizing effluent, and the degree to which effluent may be recharging drinking water tables.

Determining levels of Gd_{ANTHRO} in the annual growth rings of cottonwood trees may offer insights into these questions. For example, measuring the concentrations of Gd_{ANTHRO} in annual growth rings of trees along effluent dominated streams could reveal the degree to which riparian species utilize effluent to meet evapotranspiration requirements. Mapping the spatial distribution of trees with detectable levels of Gd_{ANTHRO} can also provide information on the dispersion patterns of effluent within the riparian ecosystem. Such insights could help inform water management efforts aimed at securing water specifically for environmental needs. Furthermore, if Gd_{ANTHRO} could be developed as a tracer for the presence of effluent in surface water, groundwater, and trees, adaptive policies could be developed to ensure that the quality in effluent is sufficient for both environmental and human uses.

Future research on Gd_{ANTHRO} concentrations within other riparian species such as velvet ash (*Fraxinus velutina*) would offer additional insights into the spatial gradient of effluent utilization and temporal differences in Gd_{ANTHRO} concentrations. More information on the impacts of effluent quality on the chemical composition of tree rings can be a useful monitoring tool to evaluate the spatial and temporal patterns of effluent use by riparian trees and to identify changes in surface water quality.

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B.8 Figures

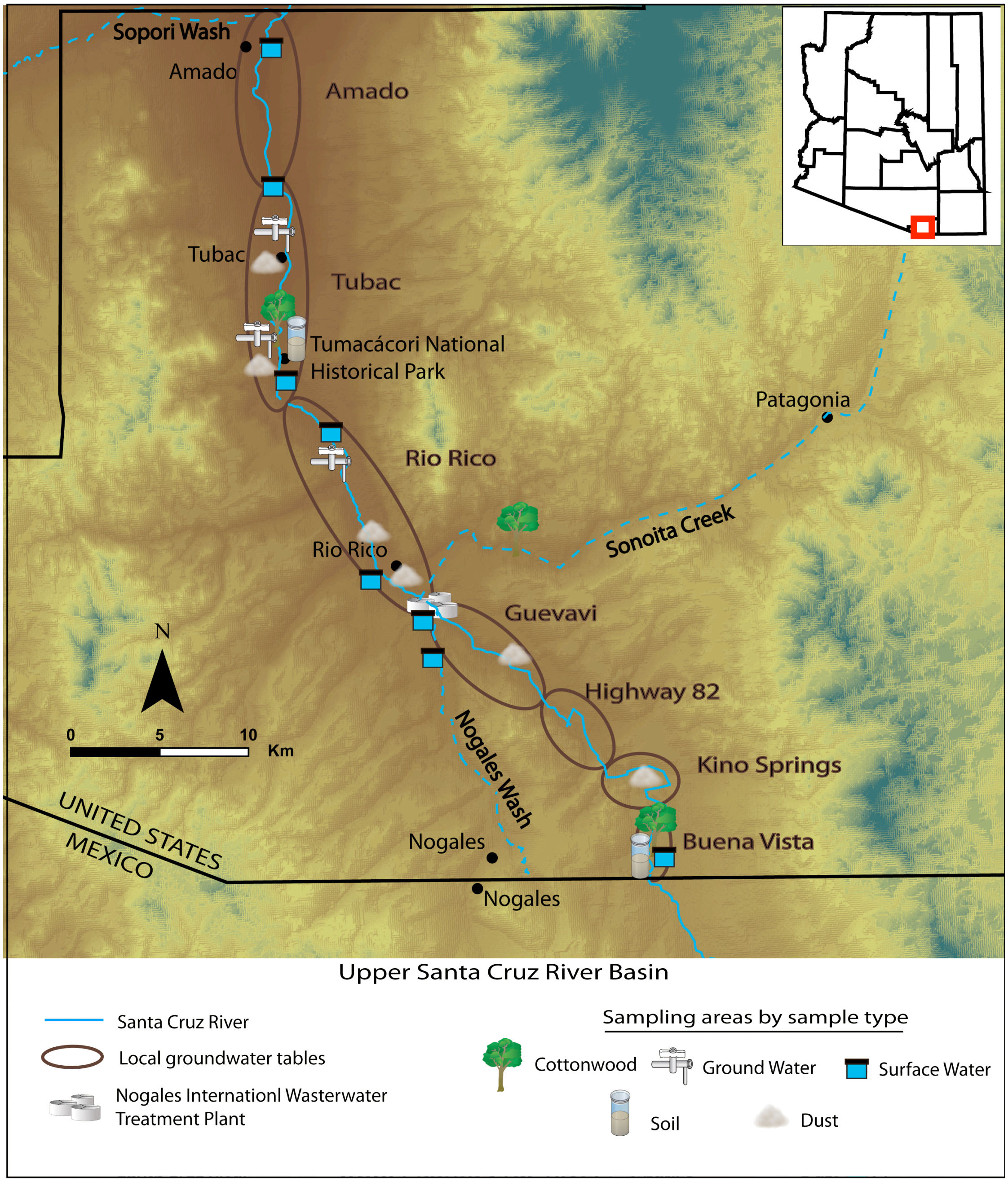

Figure B1. Upper Santa Cruz River Basin sampling locations and types.

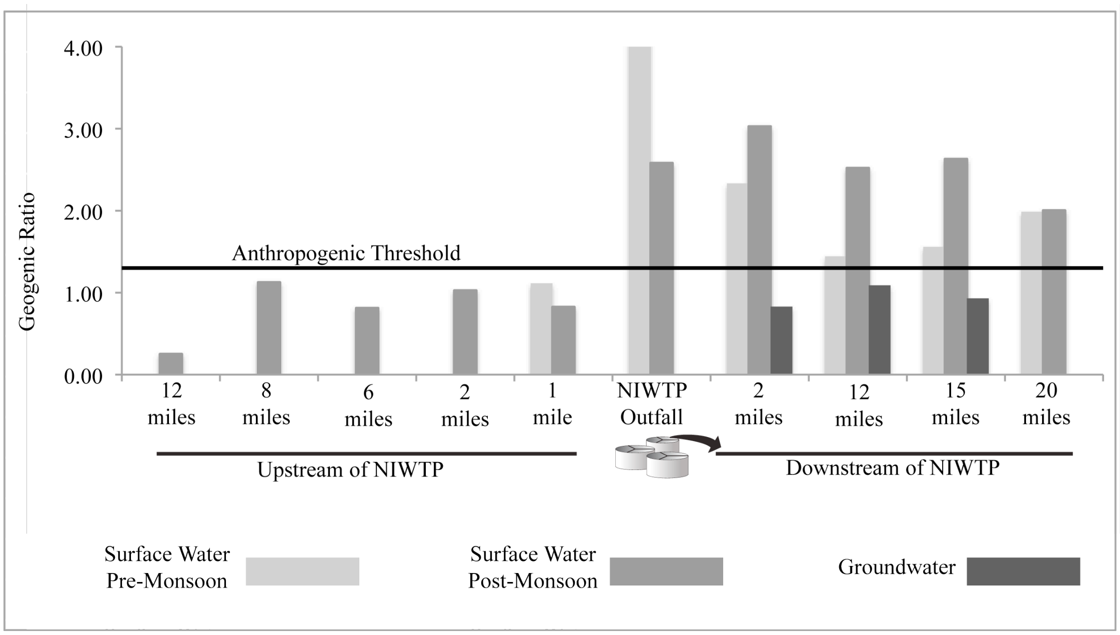

Figure B2. Geogenic Ratio in Upper Santa Cruz River surface and groundwater samples. Values above the anthropogenic threshold of 1.3 indicate the presence of Gd_{ANTHRO}.

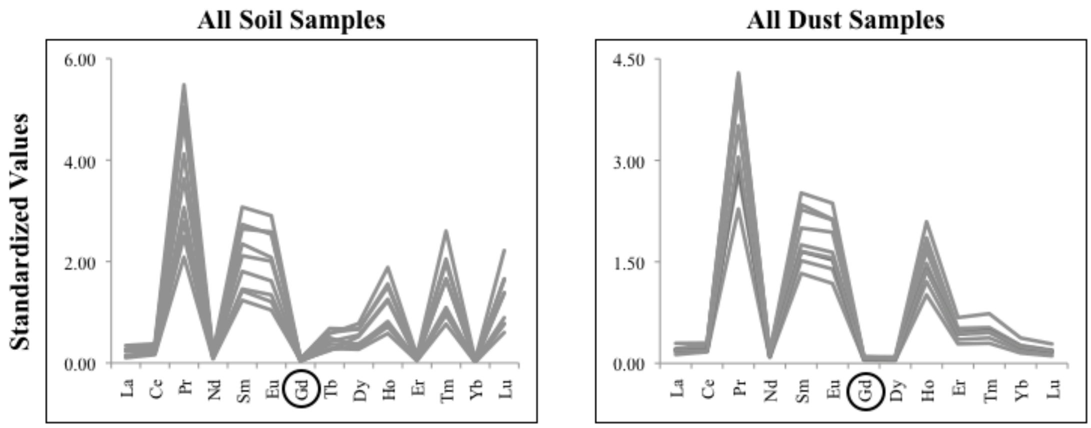

Figure B3. Standardized soil and dust samples from all sampling locations showing negligible amounts of Gd relative to other REEs.

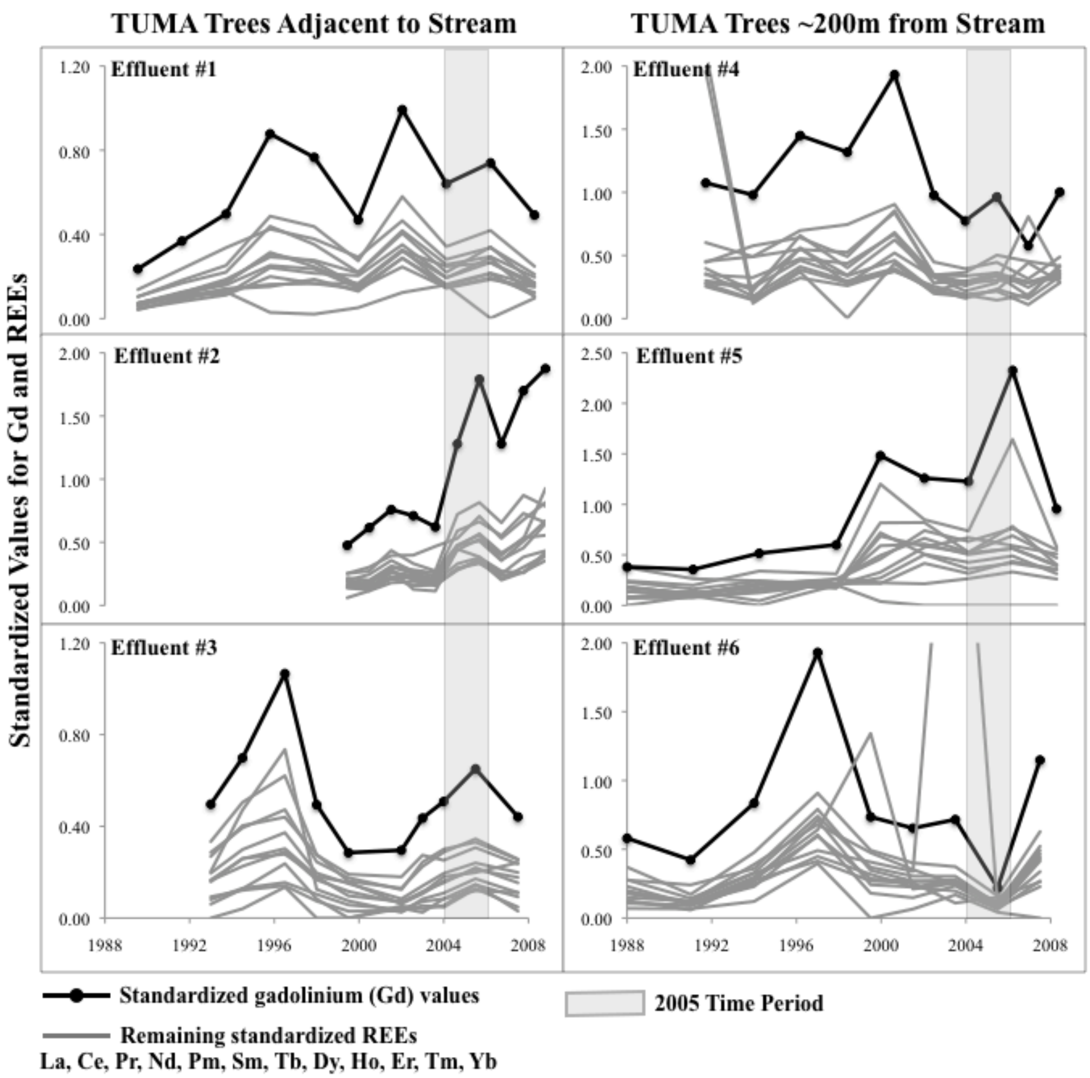

Figure B4. Relative concentrations of REEs in three cottonwood trees adjacent to the effluent-dominated stream (left column) and ~200 meters west of the effluent-dominated stream (right column). The light gray bar highlights the 2005 time period.

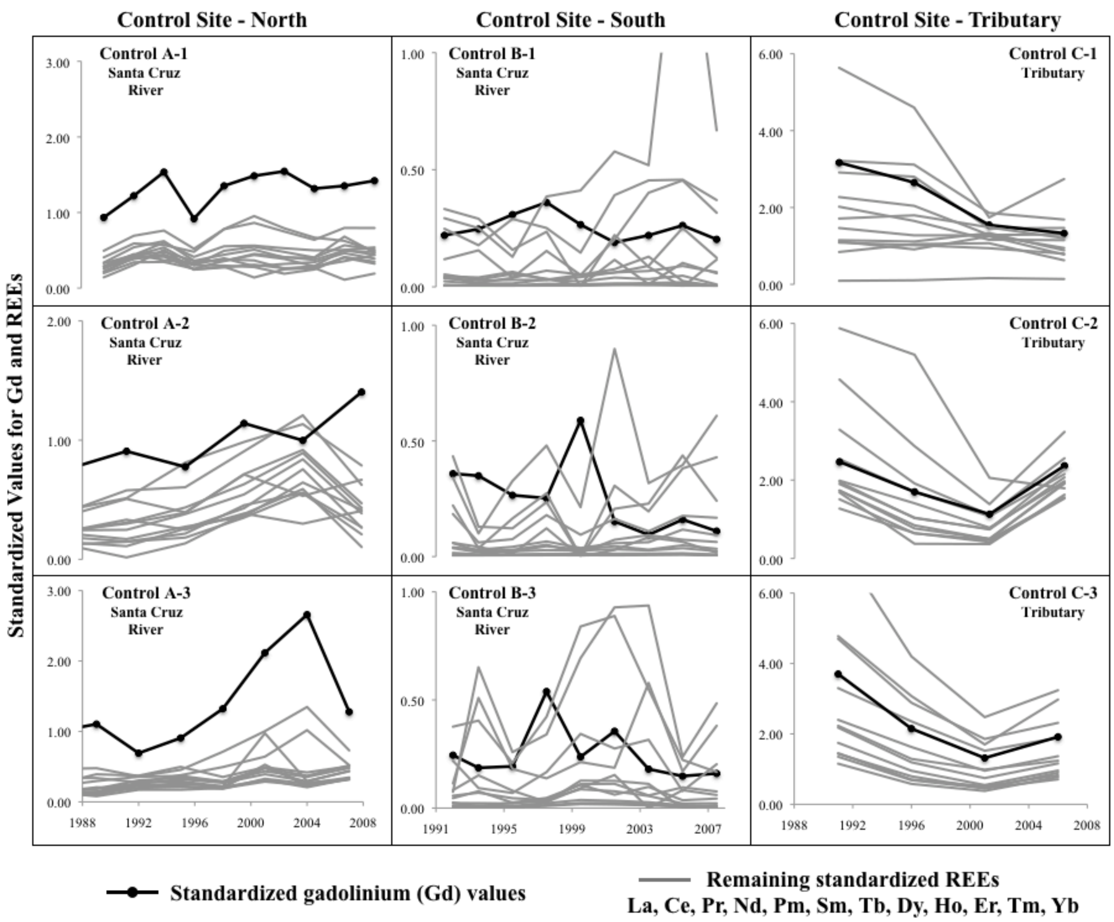

Figure B5. Relative concentrations of REEs in cottonwood trees at two control locations along the main stem of the Upper Santa Cruz River.

APPENDIX C -- IMPACTS OF EFFLUENT ON RIPARIAN RESILIENCE

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C.1 Abstract

In 2005, a significant and sudden vegetation die-off event occurred in the riparian corridor of the Upper Santa Cruz River in southern Arizona. Analysis of past and current vegetation along the river suggests that this event can be linked to two competing factors relating to the discharge of treated municipal effluent into the river. Examination of records of riparian vegetation indicates an increase in the extent and density of vegetation in the 1980s and 1990s; this increase coincided with the presence of effluent subsidies and favorable climate conditions that encouraged vegetation growth. However, while water quantities in the river supported vigorous vegetative growth, poor effluent water quality was slowly hindering hydrologic functions. Our analysis of the riparian ecosystem suggests that the 2005 event was partially due to the eventual extreme degradation of the river's hydrologic functions coupled with drought conditions of the 2000s. The die-off, in tandem with the results of this study, highlight the uncertainties and unknowns of effluent use in the Upper Santa Cruz River, further underscoring the need to develop scientific and legal mechanisms to ensure that effluent bolsters, rather than degrades, riparian function and supports the provision of riparian ecosystem services in the semi-arid southwestern United States.

Keywords: Effluent, ecosystem services, riparian vegetation, Upper Santa Cruz River

C.2 Introduction

Although freshwater resources are finite, the demands for water in municipal, agricultural, industrial, and environmental restoration sectors are growing in tandem with worldwide human population (Postel 2000, Malmqvist and Rundle 2002). Paradoxically, while urban areas require more freshwater supplies for municipal and industrial use, those same freshwater supplies are converted into voluminous amounts of wastewater that are becoming available for reuse. Wastewater, commonly referred to as treated municipal effluent, can address the pressing challenge of meeting increasing urban and environmental water demands (Brooks et al. 2006, Corwin and Bradford 2008). The growing acceptance of effluent as a viable source of water for restoring and maintaining natural riparian areas raises important questions about how riparian functions and ecosystem services are impacted by effluent subsidies, particularly against the backdrop of climate change and drought conditions.

Ecosystem services are defined as the conditions and processes through which natural systems support, sustain, and enrich human life (Costanza et al. 1997, Daily 1997, MEA 2005). Rivers and riparian areas provide crucial hydrologic services such as water purification, flood control, aquifer recharge, carbon storage, and recreational opportunities (Brauman et al. 2007). Freshwater is the primary ingredient that drives the production of these services; yet as demands for freshwater increase, changing climate conditions alter the timing, location, and extent of precipitation events (IPCC 2007).

Climate change predictions are particularly alarming for the southwestern United States, where droughts are expected to increase in frequency and severity (Cook 2004), and recent models predict a 10-30% decrease in run-off by the year 2050 (Milly et al. 2005). In order to increase water supplies, numerous urban areas in the southwest are looking to effluent as a source of water for river and riparian restoration projects (Miller 2006, Colby and Jacobs 2007) that can contribute to the maintenance of hydrologic ecosystem services.

Our study examines the effluent-dominated Upper Santa Cruz River (USCR) in southern Arizona. We frame our analysis within the context of a sudden die-off of riparian vegeation along a 16 km reach of the river directly downstream of the point of discharge for the Nogales International Wastewater Treatment Plant. We focus specifically on changes in the extent and composition of the riparian forest over time, including an assessment of cottonwood and willow vegetation before and after the 2005 die-off event. This approach applies the lens of ecosystem resilience as a way of evaluating the connection between riparian function and the provision of hydrologic ecosystem services in an effluent-dominated system.

Changing riparian vegetation patterns are analyzed in tandem with increased effluent subsidies, shifts in climate, and sub-optimal water quality. We compiled five data sets for studying these changes within the USCR ecosystem from which we base the analysis described in this paper. Our data includes (1) creation of the first riparian vegetation map along the effluent-dominated reach of the river, (2) reconstructed historical (1950-2004) vegetation conditions using aerial photography, (3) synthesized and previously unpublished water quality data, including documentation of increased nutrient concentrations, (4) effluent discharge data, and (5) compilations of regionally specific hydroclimatic information, including changing precipitation, streamflow patterns and groundwater levels. Using these data sets, we examine how riparian vegetation composition and extent has varied over time in response to effluent subsidies, how water quality and climate trends affect the role of effluent subsidies in the system, and how these factors contributed to the 2005 riparian vegetation die-off. Building from our analysis, we briefly examine how gaps in Arizona's water management framework have enabled effluent subsidies to sustain a riparian area without the necessary adaptive responses to ensure that effluent bolsters the continued provision of ecosystem services.

Given uncertainties regarding ecological stability under climate change, contemporary research is focused on managing for ecosystem resilience rather than ecosystem optimization (Peterson et al. 1998, Gunderson and Holling 2002, Folke 2006). Resilience is defined as "the capacity of a system to absorb disturbance and re-organize in the presence of stress so as to retain essentially the same function, structure, identity, and feedbacks" (Holling 1973, Walker et al. 2004). Resilience is a compelling framework for studying and understanding the USCR, the roles of effluent discharges into the river, the recent vegetation dynamics of the riparian corridor, and the prospects for future policy and management decisions. Within the context of resilience, we suggest management actions that may be needed to ensure that effluent contributes beneficially to system resilience.

C.3 Study Area

The Santa Cruz River is a unique and regionally significant watershed in the southwestern United States that hosts tremendous ecological diversity and a mosaic of cultures and history (Marshall et al. 2004). Stretching across southern Arizona and the northern portion of the Mexican state of Sonora, the Santa Cruz River is the only river to cross the U.S./Mexico border twice. From the high desert grasslands of southeastern Arizona, it flows southwards into northern Sonora, then back into Arizona where it continues for another 200 kilometers (km) before merging with the Gila River. The upper reaches of the Santa Cruz River extend from the headwaters, through Sonora, and back across the U.S./Mexico border, traversing 64 km to the border of Santa Cruz and Pima Counties. The middle and lower reaches of the river extend through Pima County and continue northward to the Gila River. This study is focused within that 64 km stretch of the river and will be referred to as the Upper Santa Cruz River (Figure 1).

The Upper Santa Cruz River (USCR), located within the Sonoran desert at the southern portion of the basin and range province, is characterized by mild winter temperatures and high summer temperatures. The average maximum temperature at Tumacácori National Historical Park (1948-2005) is 36°C and occurs during the month of July. The average minimum is 0°C and occurs during January. The USCR and surrounding areas are characterized by a bimodal precipitation regime, with most of the precipitation received in mid-summer during the North American Monsoon, followed by winter precipitation in the form of Pacific frontal storms (Adams and Comrie 1997, Sheppard et al. 2002). Average annual precipitation recorded at Tumacácori (1948-2005) is 40 cm. Two United States Geological Survey (USGS) river gauging stations on the Santa Cruz River at Nogales and Continental (located near the international border and between Tubac and Tucson respectively) provide a record of flood events and high precipitation. Major fall and winter floods occurred on the Santa Cruz River in December 1967, October 1977, October 1983 and January 1993. Prior to the flood of 1967, most peak flows were considerably smaller and occurred as a result of summer rains, indicating a change in flood seasonality during the 20th century (Webb and Betancourt 1992).

The stretch of the Upper Santa Cruz River that is the focus of this study flows from south to north across the U.S./Mexico international border. Surface flow in the river is intermittent for 16 km from the international border north to the point of discharge from the Nogales International Wastewater Treatment Plant (NIWTP). Daily discharges from the NIWTP sustain perennial flow downstream for approximately 48 km. The NIWTP began operation in the 1951 and discharged 6,057 cubic meters per day (m^3/day) (1.6

million gallons a day (mgd)) into Nogales Wash, a tributary to the USCR. In 1972, the NIWTP was moved to its current location and upgraded to a capacity of 31,040 m^3/day (8.2 mgd). A second expansion occurred in 1991, increasing the capacity to current discharge rates of 65,109 m^3/day (17.2 mgd).

The USCR is characterized by four shallow and cascading micro-basins upstream of the NIWTP and three sub-area basins downstream of the NIWTP that together form the underlying floodplain alluvium aquifer (Figure 1). These micro- and sub-area basins have low storage capacity and range in depth from 12 to 45 meters (Nelson and Erwin 2001). Due to the shallowness of the aquifer and the permeable nature of the alluvium, the basins are very sensitive to climatic changes. Water tables rise quickly during heavy precipitation events and cascade into adjacent downstream basins. Conversely, basins can rapidly deplete during droughts (Nelson 2007). Riparian vegetation is uniquely adapted to draw water from both surface flow and groundwater and is thus fundamentally dependent on shallow water tables and surface flow.

A robust riparian ecosystem extends along the 48 km effluent-dominated perennial reach of the USCR and is compromised of signature riparian tree species such as Fremont cottonwood (*Populus fremontii),* Goodding's willow *(Salix gooddingii),* Velvet ash (*Fraxinus velutina*), Velvet mesquite (*Prosopis velutina*), Arizona walnut (*Juglans major*) and Netleaf hackberry (*Celtis laevigata* var. *reticulata).* Biological inventories have recoded nearly 600 species of vertebrates and invertebrates that depend upon the river system for either temporary or permanent habitat (Powell 2004). By maintaining perennial flow in the river, effluent has also provided supplemental aquifer recharge resulting in a 0.8 meter average increase in groundwater levels for wells located downstream of the NIWTP since 1972 (Corkhill and Dubas 2007).

The USCR has known water quality issues and sections are listed as an impaired water body for one or more of the following ten pollutants: ammonia, chlorine, chlorophyll, copper, dissolved oxygen, *Escherichia coli* bacteria, mercury, nitrogen, phosphorous, and zinc (ADEQ 2008). A river or stream is designated "impaired" when pollutants have been recorded above the levels permitted by the U.S. Environmental Protection Agency (EPA) under the Clean Water Act (USEPA 2007). Of these ten pollutants, ammonia, nitrogen, and phosphorus have direct impacts on riparian ecosystem function and will be analyzed further in this study.

C.4 Upper Santa Cruz River Die-off Event

In spring 2005, sudden, comprehensive mortality of Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*) species occurred along an approximately 16 km reach of the USCR from the NIWTP to Tumacácori National Historical Park (NHP) (Figure 2). USGS streamflow gauges, groundwater levels, and precipitation data from Tumacácori NHP clearly indicate the presence of regional drought conditions and lower than average stream flows. A study of aerial photographs and satellite imagery from the previous year (2004) did not indicate that the riparian vegetation was exhibiting typical physical responses to drought or groundwater decline, 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 sudden and suggested a threshold change in vegetation composition.

An ecological threshold is defined as a point in time when an abrupt change in ecosystem conditions occurs (Odum et al. 1979, Briske et al. 2006, Groffman et al. 2006). Threshold shifts are indicative of the complex and dynamic relationships between large-scale external forces (i.e., climate) and system-specific components (i.e., water quality) that interact and trigger shifts in conditions (Odum 1985, Mayer and Rietkerk 2004) and loss of resilience (Gunderson 2000, Suding and Hobbs 2009). On the USCR, complex interactions between riparian vegetation, hydrologic conditions, climate, and effluent create the potential for threshold events such as the mortality event in 2005.

Several key studies have examined individual elements of USCR mortality event (Treese et al. 2009, Villarreal 2009). Our analysis builds on the foundation of this work by elucidating the non-linear and complex interactions between riparian vegetation, hydrologic function, effluent subsidies, and water quality data within the context of changing climate conditions. We examine how these interactions may have contributed to a threshold shift in riparian function. This analysis also considers the social components of the system and addresses how monitoring and evaluation based on ecosystem function can fill management gaps and provide a buffer against future loss of resilience and ecosystem goods and services.

C.5 Methodology

C.5.1 Riparian Vegetation Map

We integrated field and lab methods to document current riparian vegetation in the USCR using the National Vegetation Classification (NVC) system as a model (FGDC 2008). We first developed a vegetation Formation Class (dominant life form) map through aerial photo-interpretation. All vegetation was classified to the NVC Formation Class level, with one major modification: forests and woodlands were assigned qualifiers distinguishing Mesquite from Cottonwood-Willow. Three types, Riparian Woodland, Riparian Mesquite Forest and Riparian Forest, were mapped at a level between Formation Subclass and Division to include environmental and species information (Table 1). Mesquite can be accurately distinguished from other riparian species (cottonwood and willow) based on spectral and textural signals. Because the rates of establishment and life history strategies of these communities are distinct, as are their value as habitat, this important division allowed us to address in more detail riparian dynamics when applying this classifications scheme to historical aerial photographs.

We next refined the Formation Class vegetation map to an Alliance (dominant species) vegetation map through extensive field work and data collection. A total of 4,545.3 hectares (ha) (11,231.6 acres) of riparian vegetation were mapped along the main stem of the Upper Santa Cruz River and a portion of the Nogales Wash. Using information on the dominant plant species observed in the field, we described 40 unique vegetation alliances (groupings of different species) within eight dominant vegetation formations: forest, woodland, wooded shrubland, shrubland, tree savanna, shrub savannah, herbaceous, and bare ground (Table 2). The analysis presented in this paper focuses exclusively on forest and woodland riparian vegetation in the effluent-dominated portion of the river.

C.5.2 Historic Vegetation Analysis

To analyze past conditions, we mapped historical vegetation to the Formation-level using six dates of aerial photography (1936, 1956, 1975, 1984, 1996, and 2004). Because coverage of historical aerial photography is often incomplete and of varying quality, we developed a catchment-based stratification approach and mapped a subset of historical vegetation within each major catchment. Using the 2006-2007 Formation map as a reference, we compared fragmentation metrics (class and patch indices) calculated for the entire vegetation map to indices calculated for 11 catchment subsets of the same map. For most indices, we found that subsets are representative of the entire catchment and greater landscape and could therefore mitigate the varying quality of historic photography.

In the vegetation analysis for this study, we focused on the Rio Rico and Tubac sub-area basins because they were historically perennial, sustained cottonwood/willow riparian habitat, and included the area of the mortality event. Because the die-off impacted mature stands of vegetation, we identified the most complex, diverse, and mature vegetation alliances as determined by the riparian vegetation map. "Mature" is defined as a riparian forest that includes "three-dimensional structural characteristics such as large, living old trees; …relatively open canopies with foliage in many layers; and a diverse understory" (Naiman et al. 2005). Forest and woodland formations comprised of cottonwood/willow and mesquite alliances reflect this definition of mature in the numbers of trees, shrubs, and herbaceous species represented, as well as the structural complexity and diversity of the mid- and understory layers.

C.5.3 Water Quality Data

Water quality data were compiled from data gathered by RiverWatch, a water quality monitoring program initiated in 1992 by Friends of the Santa Cruz River (FOSCR). Volunteers collect samples on a quarterly basis from five locations along the Upper Santa Cruz River. A suite of water quality parameters are sampled including: pH, dissolved oxygen, nitrogen, ammonia, flow, and phosphorous. For the purposes of this study, we focus our analysis ammonia, nitrogen, and phosphorus trends due to their direct impacts on riparian vegetation growth (Marler 2001, Schade et al. 2002) and hydrologic function (Grimm 1987, Triska et al. 1993, Boulton et al. 1998). Arizona Department of

Environmental Quality (ADEQ) has verified FOSCR's monitoring protocols through an ADEQ approved Sampling and Analysis Plan. In addition, ADEQ incorporates FOSCR's monitoring data into Integrated 305b Assessment reports that describe the status of surface water in Arizona in relation to state water quality standards and in fulfillment of the requirements of the Clean Water Act section 305b. With the exception of these reports, the FOSCR's monitoring data has not previously been analyzed in tandem with climate data or in the context of riparian function.

C.5.4 Effluent Discharge Data

Effluent discharge data were acquired from the NIWTP from 1994 - 2008. Data were collected by the NIWTP and available in a daily and monthly mean format.

C.5.5 Hydroclimatic Data

Precipitation data were obtained from the Western Regional Climate Center (www.wrcc.dri.edu) for Tumacácori NHP. Data were organized into two parameters: annual totals and 10-year moving average from 1955 - 2008. Streamflow data were obtained from the United States Geological Survey Real-Time Water Data website (waterdata.usgs.gov/nwis/rt) for the Tubac, Amado, and Continental gages (Figure 1). Continental streamflow data began in 1940, Tubac data began in 1995, and Amado began in 2003. Groundwater data was obtained from the Arizona Department of Water Resources on-line groundwater database (gisweb.azwater.gov/waterresourcedata).

C.6 Results and Discussion

C.6.1 Drivers of Change: Climate and Water Quality

The results of our analysis of climate and effluent water quality indicate that their relative impacts on the health and function of the riparian corridor are linked. Favorable climate conditions dampen the negative impacts of poor water quality, but drought conditions exacerbate those impacts and significantly reduce the function and resilience of the system. Our results, as described in this section, point to both climate and water quality as the primary drivers of change in the USCR ecosystem.

Precipitation patterns in the USCR basin are consistent with larger regional climate trends. Precipitation amounts were above average in the 1980s and 1990s and then dropped significantly below average in the early 2000s in response to a well-documented regional drought (Figure 3; Cook et al. 2004, Hughes and Diaz 2008). Precipitation affects the magnitude and frequency of flood events on the river and six of the seven largest floods in an annual flood series from 1915-1986 occurred after 1960 (Webb and Betancourt 1992). Major floods in 1967, 1977, 1983, and 1993 saturated the floodplain and shallow groundwater tables, thereby providing ideal conditions for the establishment of three distinct bands of cottonwood/willow riparian vegetation in the floodplain (Webb et al. 2007). Groundwater table recharge is also tightly linked to precipitation patterns. The year 2000 was a flood-dominated year with 62 million m^3 (50,000 acre-feet (af)) of recharge, while 2002 was the start of the drought with less than 25 million m^3 (20,000 af) of recharge (Nelson 2007).

Water quality is a measure of the chemical and biological properties of a stream. Riparian ecosystems depend on specific water quality conditions to sustain plant and animal communities and variations in water quality both positively and negatively impact riparian ecosystems (USEPA 2002, Mayer et al. 2007). Nutrients such as nitrogen are essential for plant and animal life but in excess, they can decrease habitat quality and alter the composition and species diversity of aquatic communities (USEPA 2000). Levels of ammonia (NH_3) in high doses are toxic to aquatic life (USEPA 1999) and the presence or absence of fish and aquatic macro-invertebrates are visible indicators of water quality. Previous studies have identified ammonia as the toxicant responsible for native fish mortality in the USCR (King et al. 1999). We analyzed trends in ammonia levels and found that both nitrates and ammonia levels have been increasing on the USCR since 1992 (Figure 4).

Water quantity and water quality are also linked on the USCR. In addition to harming aquatic life, nitrogen can foster micro-faunal growth. This can negatively impact the hydrologic exchange between surface water and groundwater that takes place via a connecting ecotone termed the hyporheic zone (Brunke and Gonser 1997). The importance of the hyporheic zone to riparian function is well documented (Standford and

Ward 1988, Findlay 1995, Boulton et al. 1998). Micro-faunal communities that thrive in the hyporheic zone filter the water that transitions between surface flow and groundwater tables, removing contaminants and facilitating groundwater recharge (Harner and Stanford 2003). High nitrogen levels foster algae growth that can form thick mats--known as clogging layers or schmutzdecke--on the bed of the stream channel (Lacher, 1996, Hancock 2002). Periodic floods will typically scour the clogging layer. During prolonged droughts when rainfall is low and floods are rare, the clogging layer can seal the bottom of a stream channel, decreasing infiltration and recharge, reducing filtration, and hindering the connection between surface water and groundwater (Brunke and Gonser 1997).

Our analysis of water quality monitoring data shows an increase in nitrogen and ammonia levels in river water from 1992-2008 (Figure 4), providing necessary nutrition for a clogging layer. The start of the regional drought in 2002 and a corresponding dramatic decline in floods from 2002–2005 created the ideal conditions for a clogging layer to form, grow and ultimately sever the groundwater-surface water connection in the hyporheic zone. Two consecutive floods of 350 cfs are needed in the USCR to scour the streamed and remove the clogging layer (Treese 2008); these floods occurred in 2005. Immediately prior to these flood events, surface flow was measured over 40 km downstream of NIWTP. After the floods, the extent of surface flow retreated 10 km - an indication that the floods scoured the clogging layer and infiltration from the stream into the groundwater tables started again (Figure 5).

C.6.2 Impacts of Change: Riparian Vegetation Expansion Contraction

Analysis of riparian vegetation patterns on the effluent-dominated portion of the USCR illustrates an interesting pattern of riparian vegetation expansion and contraction. In the USCR, effluent flows provide additional water and nutrients to a system co-limited by both. Nutrients play a key role in supporting vegetation growth and riparian vegetation has been shown to effectively utilize nitrogen from water flowing through floodplain soils, particularly in effluent-dominated systems (Schade et al. 2002, Schade et al. 2005). While the importance of nutrient availability is not quantified for riparian systems, it is known that too little nitrogen limits vegetation productivity in terrestrial environments (Adair et al. 2004, Tibbets and Molles 2005). Therefore, increased availability of nitrogen from effluent inflows bolsters the rate of nutrient cycling as well as riparian vegetation growth and abundance along the USCR (Marler et al. 2001).

Cottonwood and willow trees are obligate riparian species that depend upon groundwater-surface water connections and fulfill their water and evapotranspiration requirements from both the unsaturated soil zone and shallow groundwater tables (Snyder and Williams 2000, Rood et al. 2003). Obligate species are sensitive to temporal and spatial changes in groundwater levels and optimal groundwater depth should not exceed 4m (Lite and Stromberg 2005). Natural streamflow variability is the main organizing force in the biotic composition, structure, and function of this formation (Busch et al. 1992, Scott et al. 1997). The life cycles of obligate species are dependent upon disturbances such as floods to maintain successional growth stages, to distribute seeds, and to recharge groundwater tables (Poff et al. 1997, Levine and Stromberg 2001). As a result of these ecohydrological requirements, obligate species are simultaneously adapted to disturbance such as floods and are highly sensitive to drought conditions that limit flood flows and lower groundwater tables.

In the Rio Rico sub-basin, the extent of cottonwood/willow vegetation increased steadily from 1956 through 1996 concurrently with favorable climate conditions and an increase in daily effluent amounts during that time. Analysis of cottonwood/willow vegetation in the Rio Rico sub-basin shows a slight decline from 1996 to 2004 and then a precipitous decline from 2004 to 2006 (Figure 6). The cottonwood/willow vegetation contracted from 52.6 hectares to 29 hectares over the course of two years causing a rapid change in conditions along the length of the sub-basin reach.

This is contrasted against the Tubac sub-area basin, which also experienced an increase in cottonwood/willow vegetation in the 1980s and 1990s, but did not show a similar contraction of cottonwood/willow during the threshold event in the Rio Rico basin from 2004 to 2006. Tumacácori NHP is positioned above a spring that is fed by mountain front recharge from the Tumacácori Mountains to the east (Nelson 2007). This spring provides some buffer against the perturbations of drought and the clogging layer.

Mesquite trees are facultative species typically found growing in closed canopy forests, or bosques (Spanish for "woodland") that are elevated on terraces above the active floodway and obligate riparian trees such as cottonwood and willow. Velvet mesquite is a facultative riparian species and fulfills its water and evapotranspiration requirements by utilizing primarily groundwater (Scott et al. 2000) at optimal depth to groundwater for mesquites not greater than 9-12 m (Stromberg et al. 1996). Due their ability to tap groundwater at deeper levels than cottonwood/willow trees, mesquite can more effectively withstand lowered groundwater tables and drought. However, mesquites, like cottonwood/willow, have benefited from the infusion of effluent into groundwater tables and increased threefold from 18-65 hectares in the Rio Rico sub-area basin from 1950-2006. A similar, though less dramatic, increase can be seen in the Tubac sub-area basin as well, with a change from 96-132 hectares between 1950-2006.

C.7 The Perfect Storm: 2005 Vegetation Mortality Event

While it is not possible to state precisely which factors were most responsible for the 2005 riparian mortality event, the available data analyzed in this study suggest a confluence of ecohydrological conditions that resulted in a threshold event. An infusion of nutrient-rich effluent beginning in the 1970s provided water and nitrogen to a riparian system limited by both. The effluent subsidy bolstered vegetation growth, extent, and evapotranspiration requirements. By the late 1990s, the overall extent of cottonwood/ willow forest in the three sub-basins downstream of the NIWTP had increased compared to the 1980s. In addition to effluent subsidies, favorable climate conditions produced high volume floods in 1977, 1983, and 1993 that recharged groundwater tables and provided ideal conditions for the growth of native riparian vegetation (Webb et al. 2007).

The expansion of cottonwood/willow vegetation was progressing while high nutrient levels in the effluent simultaneously supported the formation and growth of a clogging layer in the stream channel of the Santa Cruz River. Transmissivity within the effluent-dominant reach of the river normally allows for tightly coupled interactions between streamflow and groundwater levels that support both gaining and losing reaches, depending upon the frequency of flood events and groundwater levels. However, drought conditions greatly reduced precipitation and there were no significant flood events from 2001 through 2005. During this time, groundwater levels in the Rio Rico sub-basin dropped precipitously as pumping rates were maintained and mountain front and streambed recharge rates decreased. Under favorable climate conditions, this clogging layer is routinely scoured by high intensity flood events. However, due to the drought conditions, the clogging layer continued to grow and expand in the absence of floods from 2001-2005 and increasingly prevented infiltration from the stream channel into the groundwater tables and floodplain that supports the riparian forest.

The presence of a clogging layer in the USCR has significant impacts on riparian functions that are manifest in cottonwood/willow vegetation patterns. Due to the tightly coupled relationship between groundwater and surface flow in the Rio Rico sub-basin and its location directly downstream of the NIWTP, the cottonwood/willow vegetation within this sub-basin was particularly responsive to the impacts of the clogging layer. Cumulative impacts from the increased energy requirements from a bolstered riparian forest, severe drought conditions, and the clogging layer likely converged to cause a threshold event and within less than one year, the health of the cottonwood/willow vegetation crashed and there was widespread mortality within the basin.

This die-off event highlights the paradoxical nature of effluent-dominated systems: while effluent can bolster riparian vegetation growth, poor water quality can degrade hydrologic functions to the point of vegetation mortality. Natural hydrologic regimes tend to create heterogeneity in riparian ecosystems that enables the system to adapt and recover from perturbations like floods and water stress. Effluent, on the other hand, due to its consistent delivery of nutrients and water, homogenizes the system and diminishes its resilience to perturbations and stress. Subsidies of nitrogen from effluent inflows are capable of "overloading" the system by providing a water and nutrient buffer against drought and supporting a robust riparian vegetation community until the energy requirements of the system exceed available resources. This condition reflects E.P. Odum's theory that explains how systems are impacted by "subsidies", or supplemental additions such as effluent to a certain ecosystem (Odum et al. 1979). While many subsidies may have beneficial results, such as additional nitrogen in a nitrogen-limited system, at some point those additions may allow the system to increase its energy demands beyond what can be sustained by the functions and processes in place. These increased energy demands may become especially onerous during a disturbance event or perturbation, such as drought coinciding with the formation of a clogging layer (Figure 7).

In the USCR, supplemental nutrients and water provided by effluent masked the impacts of drought and muted the normal physiological response to water stress. Nutrients from the effluent bolstered vegetation production and ultimately shifted the energy requirements beyond that which the ecohydrological system could support. The riparian system was therefore less resilient and cottonwood/willow vegetation contracted in 2005. This increase and subsequent decline in riparian conditions reinforces the need to monitor and manage the quality of effluent to ensure that it is supporting, rather than hindering, riparian function.

C.8 Ecological Monitoring: Enhancing Resilience

From the results of this study we assert that effluent is paradoxical. By providing a consistent flow of water and nutrients, effluent has the potential to significantly bolster riparian vegetation growth. This increase in biomass can augment the production of hydrologic ecosystem services such as flood control and carbon storage (Brauman et al. 2007). However an increase in riparian vegetation results in higher energy requirements that are more difficult to fulfill during times of ecological stress. Additional complications such as poor water quality and drought combine to reduce hydrologic functions and reduce the overall resiliency of the system.

This ecological paradox is framed within a social structure that benefits from ecosystem services produced by a functional and robust riparian area but does not contain a legal framework that protect the riparian ecosystem. Arizona's complex institutional framework focuses on ensuring adequate water supplies for human use and consumption. Despite the importance of rivers and riparian areas to local economies (Bark et al. 2009), there are no state laws in place that specifically protect riparian systems. However, laws do exist that allow for effluent to be "abandoned" into streambeds and waterways and by default, support functioning and otherwise unprotected riparian habitat.

Under Arizona water law, effluent is considered neither groundwater nor surface water, but a separate source of water, the allocation and management of which is still evolving (Pearce 2007). Effluent is the only unallocated water source in the USCR valley (Tellman 1992). As a result of a 1989 court case, *Arizona Public Service Company v. Long* (1989), effluent may be sold by municipal and county governments and private sewer utilities for use as a non-potable water supply for golf courses, parks, and common-area irrigation in new planned developments. These arrangements require a distribution system to transport the effluent from the treatment facility to the point of use. In the absence of infrastructure and/or agreements, effluent is generally discharged directly into a stream channel, as is the case with effluent discharged from the NIWTP.

International Boundary Water Commission Minute 294 (1995) stipulates that Nogales, Sonora is permitted 37,476 m^3/day (9.9 mgd) of treatment capacity at the NIWTP and owns the right to the full 37,476 m^3/day (9.9 mgd) of treated effluent. The Arizona communities of Nogales and Rio Rico share a total of 19,306 m^3/day (5.1 mgd) of treatment capacity at the plant, and Nogales, Arizona has the right to use 16,656 m^3/day (4.4 mgd) of treated effluent. If Nogales, Sonora and Nogales, Arizona do not capture and re-direct their allocation of treated effluent before it leaves the NIWTP, then the NIWTP becomes the legal owner of the effluent. If the effluent is discharged into the Santa Cruz River and the NIWTP does not maintain dominion and control over it, then the effluent becomes eligible for appropriation under surface water law (ADWR 1997). However, neither Nogales, Sonora, Nogales, Arizona, nor the NIWTP are obligated to continue discharging effluent into the streambed even if the water has been appropriated. As a direct result, no applications for appropriation of effluent have been filed to date since there is no guarantee the right holder would receive the water supply.

The USCR is managed under the jurisdiction of the Arizona Department of Water Resources in a specially designated Active Management Area. The management plan for the USCR notes that effluent "generated by the treatment plant is one of the most important renewable water supplies in the Santa Cruz Active Management Area" (ADWR 2000). A study of the implications of sustained drought in the Upper Santa Cruz found that, "achieving safe yield would likely be impossible if the effluent from Mexico was not included" (Morehouse et al. 2000). In addition to supporting surface flow, consistent discharge from NIWTP into the Upper Santa Cruz River is the major source of recharge for the floodplain aquifer in the valley (Scott et al. 1997). Since current levels of groundwater pumping would likely eliminate most of the river's riparian habitat in the absence of NIWTP flows, effluent generated by the NIWTP represents a critical water source for meeting the current and future needs of the riparian corridor in spite of the fact that there is no legal guarantee that effluent will continue to flow in the Upper Santa Cruz River.

The paradox of effluent therefore extends through both the ecological and social systems of the USCR. Effluent can both enhance and hinder ecological functions; in either circumstance there is not a legal guarantee for its continued flows. Several proposals have been developed to secure the effluent from Mexico for continued use in Arizona through international and local negotiations (Sprouse 2003, Sprouse 2005). The success of these proposals hinges on the degree to which the public values the effluent, and those values will be determined by the degree to which effluent can help riparian health and resilience.

A robust and thorough ecological monitoring program capable of tracking annual changes in ecological functions related to the provision of specific ecosystem services could provide the information necessary to manage effluent for all potential services. Well-defined indicators of riparian function that can be measured on short (annual) and long-term intervals (decadal) can begin to address ecological uncertainties from climate change and water quality issues in effluent. These functional indicators can then be linked to the production of ecosystem services, can help quantify system resilience, and can direct policy efforts towards adapting to change and accommodating uncertainties. Ultimately, an ecosystem services operating framework that integrates social values (as expressed in economic terms) and ecological function (as the provision of services that can be measured and valued) may offer an opportunity to maintain the resilience of the system.

C.9 Conclusion

Managing river systems in the southwestern United States is becoming increasingly complex due to human impacts, multiple and competing water needs, and climate variability. Threshold changes in riparian function are particularly noteworthy because they call into question our previous assumptions and perceptions that ecosystems are inherently stable and that change is possible to control. River systems, both natural and effluent-dominated are simultaneously complex and adaptive, but are nonetheless vulnerable systems. They do not respond to change in a smooth and linear manner; rather stress can cause a system to shift from an outwardly stable state to an alternate state that may be undesirable, and shifting the system back could be difficult, if not impossible.

An analysis of riparian vegetation on the Upper Santa Cruz River in southern Arizona illustrates an increase in extent and density in the 1980s and 1990s as a result of effluent subsidies and favorable climate conditions. In the shadow of robust vegetation growth, poor effluent water quality was slowly degrading aquatic populations and hindering hydrologic functions. These opposing sets of conditions collided in 2005 in the form of a significant riparian vegetation die-off event that highlighted the uncertainties and unknowns in this system and point to the need to develop scientific and legal mechanisms to ensure that effluent contributes to, rather than degrades, riparian function and the provision of riparian ecosystem services.

C.10 References

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C.11 Figures

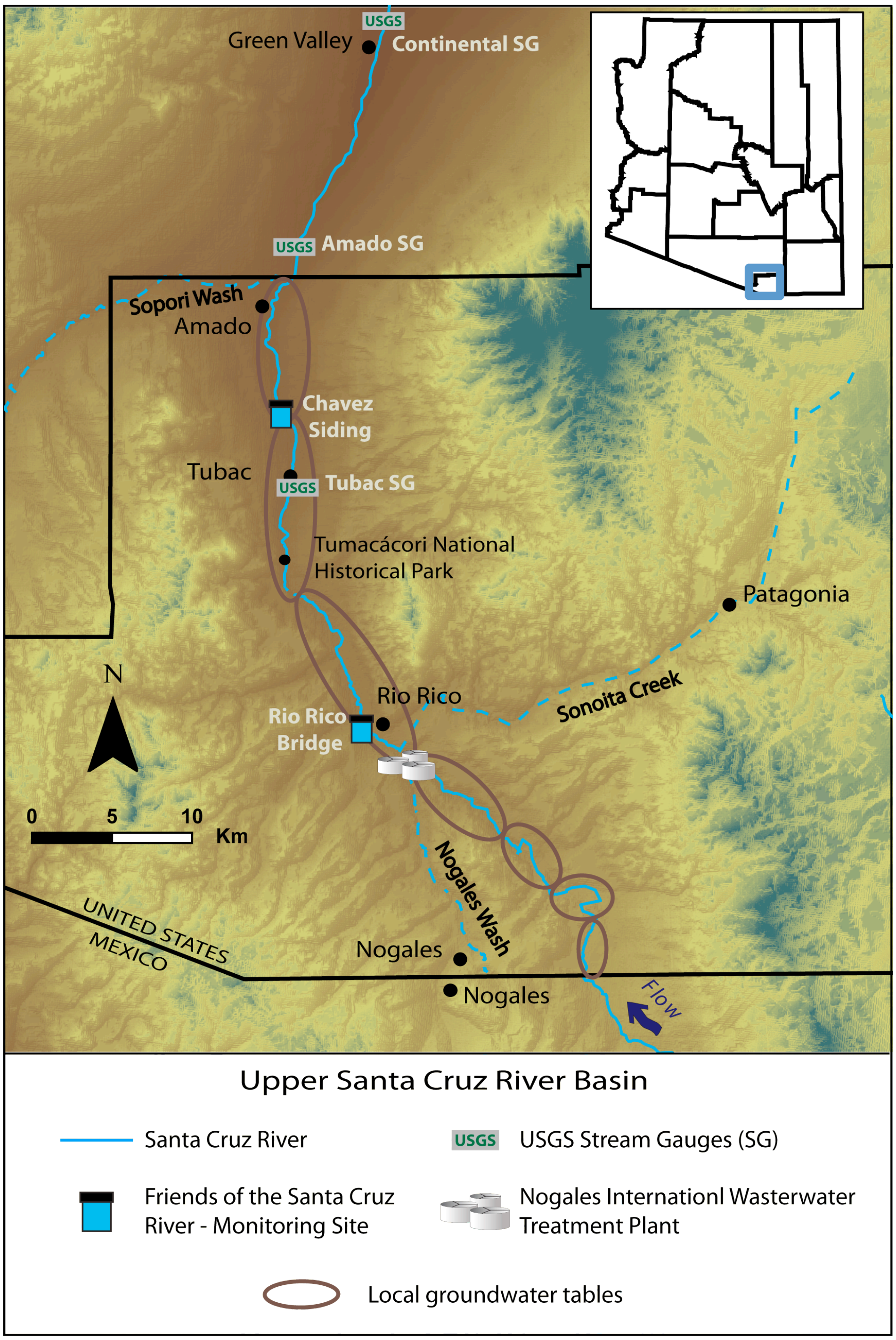

Figure C1. Map of the Upper Santa Cruz River Watershed showing water quality sampling locations and USGS stream flow gages.

Figure C2. Aerial photograph of the 2005 riparian die-off event. © Murray Bolesta

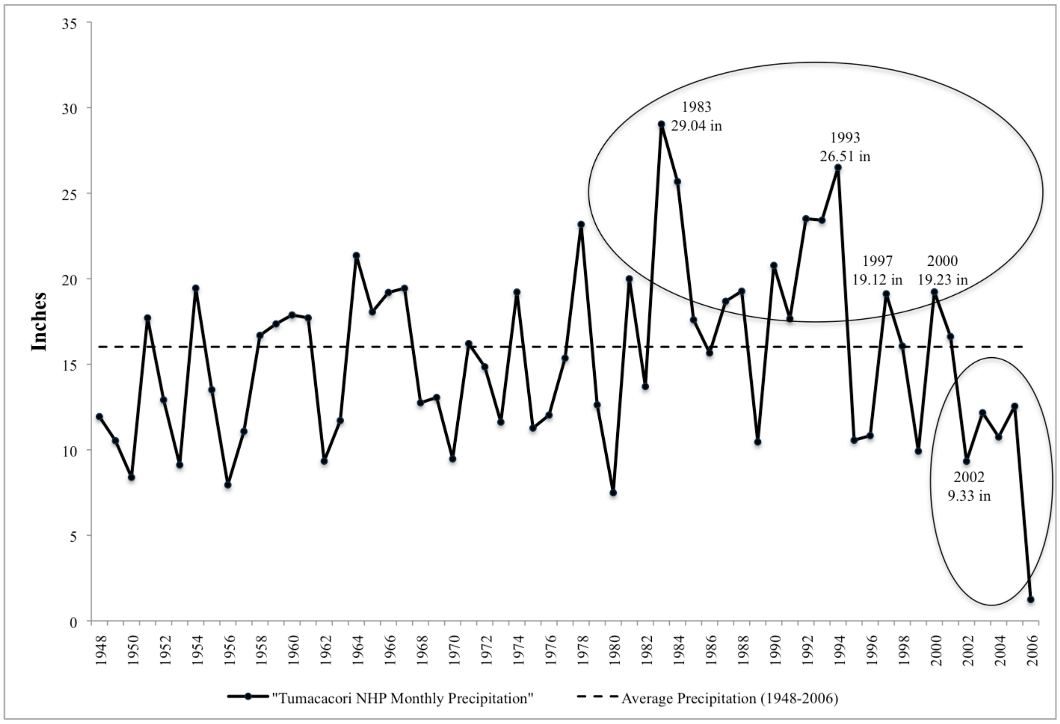

Figure C3. Annual precipitation at Tumacácori National Historical Park from 1948-2006. Areas circled include above average precipitation years in 1980s and 1990s and the drought years beginning in 2002. The dotted line represents the average amount of precipitation for the time period.

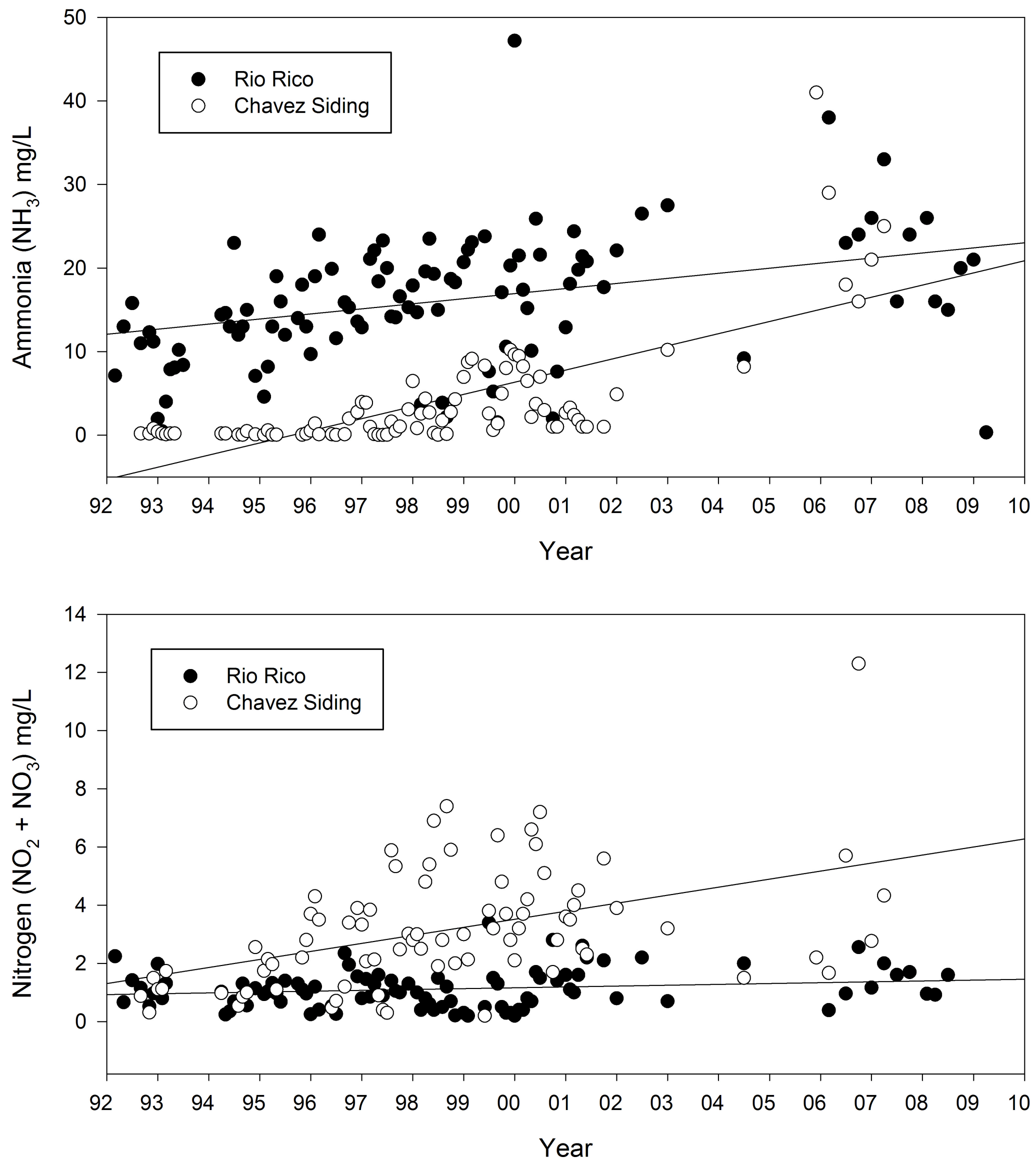

Figure C4. Increasing trends in nitrogen and ammonia at two sampling locations in the effluent-dominated portion of the Upper Santa Cruz River.

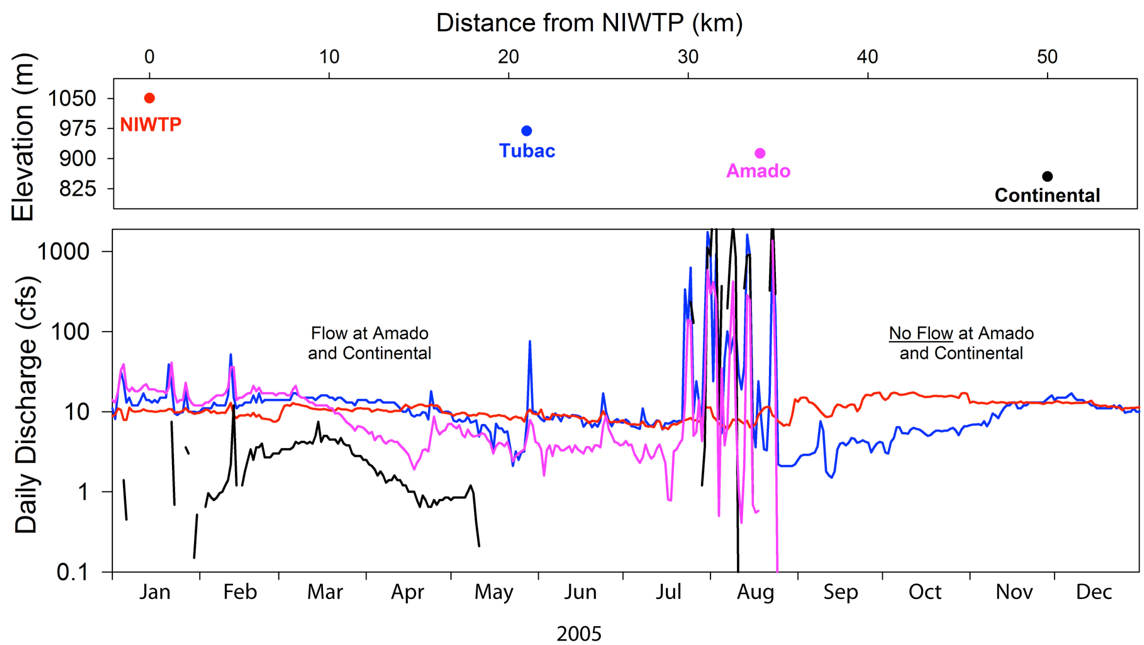

Figure C5. Clogging layer conditions in 2005. From January - May, there were consistent flows at Amado and Continental gaging stations, approximately 33 and 37 km downstream of the NIWTP, respectively. After significant flood events in 2005, the clogging layer was scoured and flows at Amado and Continental ceased.

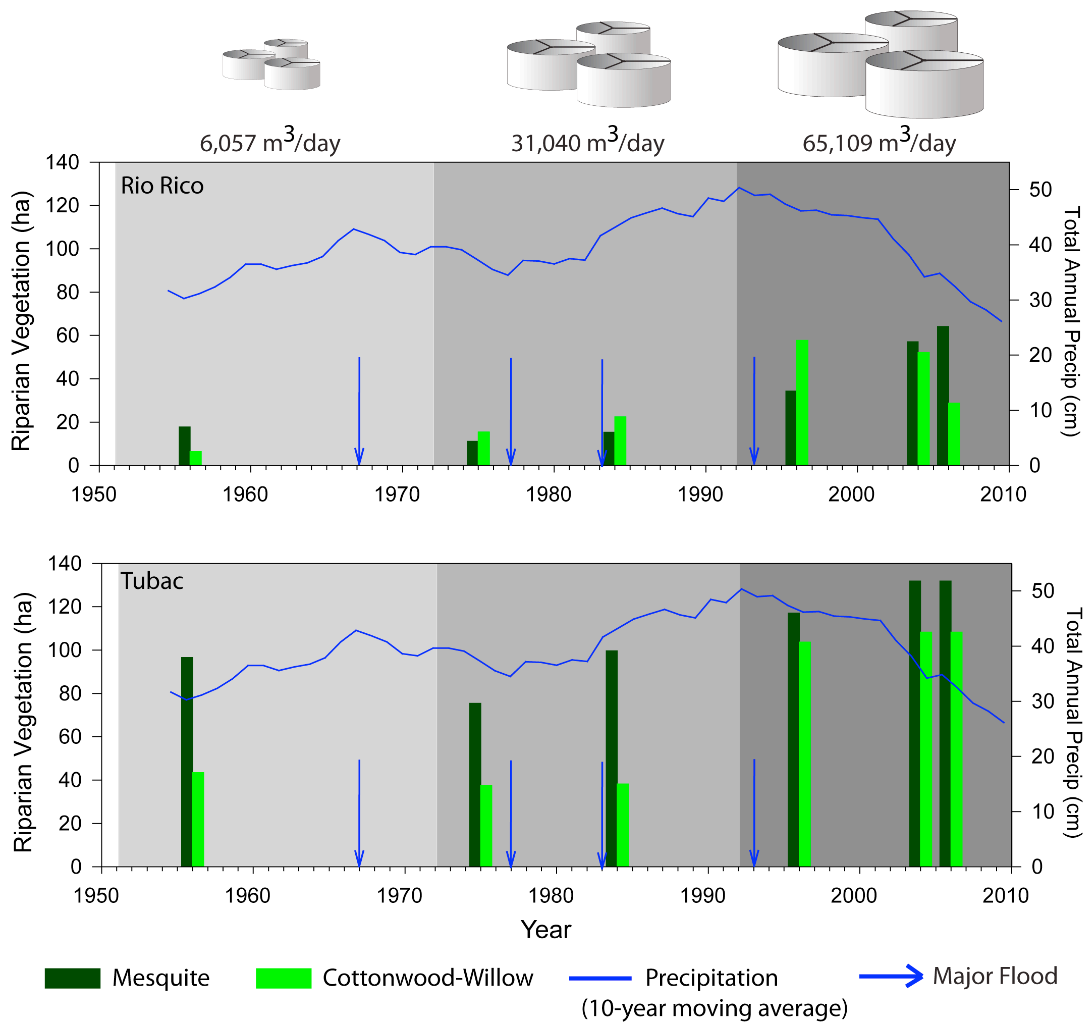

Figure C6. Riparian vegetation patterns from 1956 - 2006 plotted against a 10-year precipitation moving average for Tubac and Rio-Rico sub-area basins along the effluent-dominated portion of the Upper Santa Cruz River. Shaded gray areas represent NIWTP upgrades that included an increase in treatment capacity. Arrows indicate major flood events in 1967, 1977, 1983, and 1993.

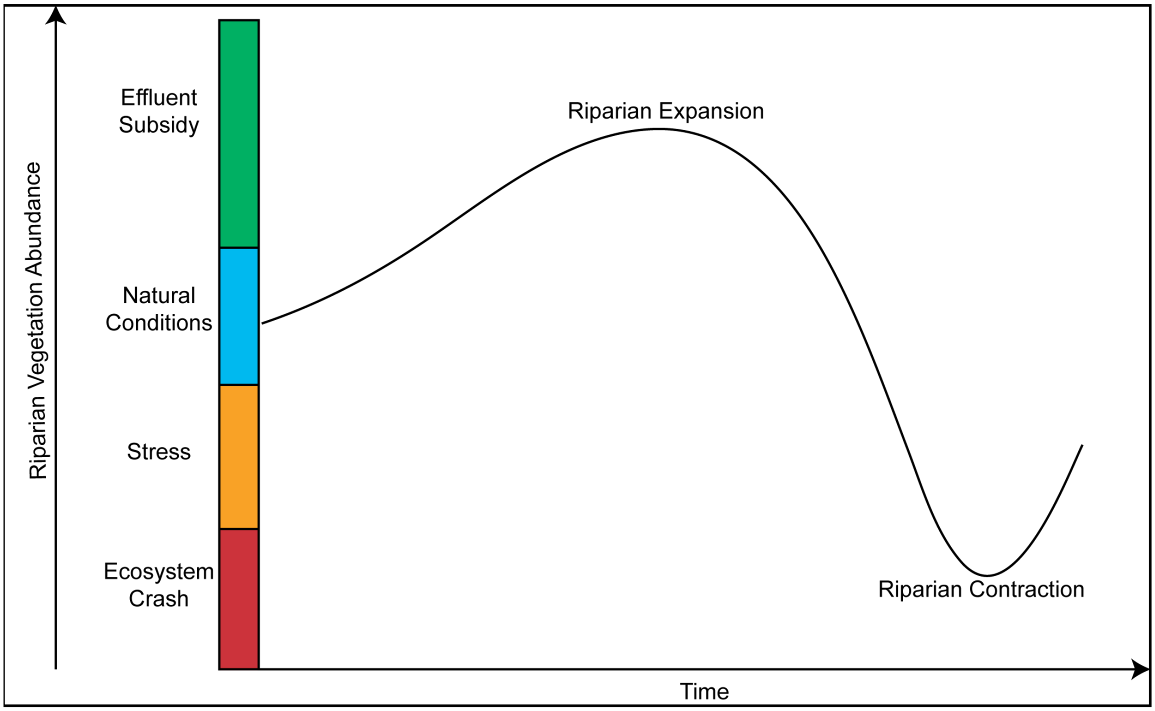

Figure C7. Subsidy-stress curve for an effluent-dominated system. Modified from (Odum et al. 1979).

Table C1. Formation Classes for the 2006-07 Santa Cruz riparian vegetation map, related National Vegetation System Formations and descriptions. The vegetation map Formation Classes generally adhered to NVC conventions with the exception of Riparian Mesquite Forest, Riparian Forest and Riparian Woodland which are closer to NVC Formation Subclasses.

Formation Class	NVC Formation	Formation Class Description
Agriculture	Agriculture	Row crops, orchards, and pasture
Barren	Barren	Rock, bare soil, and strand
Herbaceous	Herbaceous	Herbaceous dominated Tree cover < 10%, Shrub cover < 10%
Riparian Mesquite Forest	Forest	Tree cover > 60%, Mesquite dominated
Woodland	Woodland	Tree cover dominant cover type but < 60% total cover
Riparian Forest	Riparian Forest	Tree cover > 60%, Fremont cottonwood and Goodding's willow dominated
Riparian Woodland	Riparian Woodland	Tree cover < 60%. Fremont cottonwood, Goodding's willow, and Netleaf hackberry dominated
Shrub Savanna	Shrub Savanna	Herbaceous dominated, shrub cover present but < 10%
Shrubland	Shrubland	Shrub cover > 50%
Tree Savanna	Tree Savanna	Herbaceous dominated, tree cover present but < 10%

Table C2. Summary of the number of polygons and area mapped in each of the eight formations along the Upper Santa Cruz River riparian corridor. Bold, italicized text indicates the forest and woodland formations that were the focus of this study.

Formation	**Number of Polygons**	**Total Area (ha)**	**Total Area (acres)**
Forest	***185***	***971.7***	***2,401.1***
Woodland	***138***	***907.6***	***2,242.5***
Wooded Shrubland	17	65.1	160.8
Shrubland	46	191.3	472.7
Tree Savanna	86	430.7	1,064.2
Shrub Savanna	41	336.9	832.4
Herbaceous	61	332.3	821.2
Strand	24	170.9	422.5
Grand Total	598	3,406.5	8,417.3