DESERT FORESTS AND RIPARIAN FLOWS:
TRACING SOCIAL-ECOLOGICAL TRANSFORMATIONS IN THE TRANSBOUNDARY
SAN PEDRO RIVER

by

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This dissertation began on the banks of another river in Sonora, the picturesque and storied Rio San Miguel. During long walks beneath the dense canopy of the San Miguel’s riparian corridor and white knuckled drives through the turbulent topography of its deep winding valleys carefully navigating boulder-sized potholes, over cafecitos with local ranchers in their adobe kitchens and long conversations in lush gardens overflowing with fruit trees, rose bushes, and the occasional curious peacock, and sharing cervezas and homemade helados with CNH-project colleagues on warm summer nights punctuated by occasional claps of monsoon thunder, my love of Sonora, its waterways and riparian forests, and ultimately, the impetus for this dissertation, was born.

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ABSTRACT

This dissertation aims to advance understanding of the social and ecological dynamics that transform riparian forests and the human and non-human communities that depend on riparian resources. The four articles that comprise this dissertation examine the causes and consequences of social-ecological transformations in the riparian zone of the transboundary San Pedro River watershed, located in the Sonoran Desert borderlands of southern Arizona, USA and northern Sonora, Mexico. The research utilizes an interdisciplinary, mixed methods approach that combines interviews with key informants (including natural resource managers, ranchers, local residents, and political figures), archival research and historical document review, spatial analysis and synthesis of binational datasets, and land use classification and change detection at the watershed scale using methods from remote sensing and geographical information systems.

This research is motivated by two objectives. First, I aim to examine how shifts in social and ecological systems have transformed riparian spaces in the transboundary San Pedro River watershed. Second, I intend to assess the consequences of these riparian transformations for the human and ecological communities who depend on riparian resources for survival. Based on these two overarching objectives, there are three interrelated research questions that drive the research and analysis presented in the four chapters of this dissertation: 1) How are social-ecological processes at the watershed scale affecting access to water resources in the riparian zone?; 2) How are shifting relations of access to water and riparian-zone resources influencing and differentiating levels of exposure to hazards over space and across time?; and 3) Following a disturbance event, how are capacity to respond and recover from disturbance and expectations of accountability shifting over space and across time?
The findings of this research suggest three broad results. First, social processes of accumulation of land and water resources by the state and industry are creating uneven spatial and temporal experiences of water security and insecurity by shifting the amount, timing, and quality of water resources available and who can physically access the riparian zone to derive benefits from riparian resources. Specifically, the three social processes of resource accumulation that I examine are privatization, expropriation, and conservation. Second, transformations in social-ecological system (SES) dynamics and access to riparian resources differentially impact the production of water insecurity (water quality and water quantity) both between and within communities and economic sectors that depend on riparian resources. Third, the ability for local communities and small-scale agricultural producers to cope with increasing water insecurity and respond to disturbance events is decreasing due to three interrelated causes. The first is limited access of local communities to the wealth and adaptive assets produced from natural resource extraction in the region. The second is the shift at the state and community level toward increasing individuation of responsibility for ensuring livelihood security. And the third is a culture of evasion of accountability to remediate ecological degradation within the transnational mining industry.
INTRODUCTION

“Borders are set up to define the places that are safe and unsafe, to distinguish us and them. A border is a dividing line, a narrow strip along a steep edge. A borderland is a vague and undetermined place created by the emotional residue of an unnatural boundary. It is in a constant state of transition. The prohibited and forbidden are its inhabitants.” (Anzaldúa 1987: 25)

In the late nineteenth and early twentieth centuries, American and Mexican ranching and mining expertise and material traveled fluidly across the international border along the contours of the San Pedro River (Figure 1), in stark contrast to the material and ideological divisions that exist between the U.S. and Mexican sides of the watershed today. The transnational connections were so deeply embedded in local relations that the international border was referred to as an ‘imaginary’ line (Truett 2006). During the 1800s it was not unusual for ranchers to maintain legal access to lands on both sides of the unfenced, and in many places wholly unmarked, international border. Moving fluidly through the borderlands, communities forged intimate transboundary ties and established cattle grazing practices founded on binational mobility. For example, cattle moved seasonally between Arizona and Sonora, with ranchers and cowboys following close behind. Even after the passage of the McKinley Tariff by the United States government in 1890, imposing import duties on cattle crossing the international border into Arizona, the local custom of transboundary grazing in the San Pedro River valley continued. Although following the year 1890, when Customs officers became a more visible presence on the border, cowboys and their cattle were still often allowed to cross unhindered for grazing purposes.
In 1904, Colonel William Greene controlled 30,000 acres of ranchland in southern Arizona and 750,000 acres in northern Sonora, Mexico, covering the majority of the binational upper San Pedro River watershed (Sonnichsen 1974). The Arizona ranchlands under Greene’s control were portions of two historic Spanish land grants, the San Juan de las Boquillas y Nogales and the San Rafael del Valle. In Sonora, Greene’s large private estates (latifundio) had belonged to the Elías family during the second half of the 1800s, but ownership of the land was transferred to Greene in 1901 to establish the Cananea Cattle Company. In 1905, Greene established the Greene Gold & Silver Company, marking the birth of the copper mine in Cananea, today the largest copper mine in Mexico and owned by the transnational corporation, Grupo México. At the turn of the twentieth century, the prevailing view of nature was of a provider of inputs ripe for exploitation to meet economic and industrial development goals. Text from the application submitted to the Mexican government in 1903 to establish the Greene Gold & Silver Company clearly explicates the sole motivating goal of exploiting natural resources for economic development.

"The aims and objects of the Society are: To acquire, own, lease, buy in any legal form and develop and work with mines of gold, silver, copper, lead, coal or any other mineral substance and exploit, lease and sell such mines….To build, own, operate and lease or transfer in any form, pipelines, aqueducts and canals to provide and sell water. Hire, lease and sell water and water grants or concessions with their water deposits and conjoining land at the same company, drawing water from wells or any other system…To buy, acquire, sell and lease agricultural land, minerals and forests, and metals or mineral stone deposits and all classes of useful
substances for the functioning of the mines.” (Archivo General del Estado de Sonora, translation by author)

However, the exploitation of natural resources for economic gain, through cattle and mining booms, had deleterious ecological effects. By the 1940s, the exotic mix of jaguar, black bear, and wolf – comprising the San Pedro River’s unique ecosystem – had been eradicated in a campaign to make the land safe for cattle and mining activities.

In the following decade, during the presidency of Adolfo Ruiz Cortines (1952-1958), Mexico experienced a wave of agrarian unrest with more than two hundred thousand landless peasants (campesinos) nationwide calling for the creation of new ejidos - communities that manage and cultivate land in common - through land redistribution under Article 27 of the 1917 Mexican Constitution. During the decade, the Sonoran newspaper, El Imparcial, reported two thousand community solicitations for new ejido communities across Sonora, with multiple solicitations in 1953 and 1954 for the creation of ranching ejidos in the San Pedro River. These pleas went unanswered.

In 1957 and 1958, radical agrarian reform leader, Jacinto López, and the leaders of the Unión General de Obreros y Campesinos de México (UGOCM) led a series of invasions on the Greene latifundio. Land invasions and occupations were popular strategies of socio-territorial resistanceto combat the illegal continued existence of large private land estates, foreign-owned industries and absentee landlords, which were supposed to be prohibited in Mexico under the post-Revolution 1917 Constitution. The June 1958 invasion only lasted a week before Jacinto Lopez and other leaders were arrested and imprisoned. Yet, fearing growing levels of campesino unrest, a few months later President Ruiz Cortines expropriated the Greene latifundio. However,
he refused to transfer the land to the people in the form of ejidos, instead turning the land over to the Mexican state.

In February 1959, at the beginning of President López Mateo’s term in office, the expropriated Greene land, totaling 261 thousand hectares, was divided into 7 collective cattle communities (Figure 2). These seven ejidos were the first in Mexico devoted to ranching. The land was divided so that each individual within the ejido would receive approximately 300 hectares of land. In semi-arid environments, cattle grazing necessitates very large tracts of land as forage is limited. For example, stocking rates published by the Mexican agency SAGARPA in 1986, quote stocking rates of 16 hectares of land in good-condition per head of cattle. Based on these stocking rates and assuming good quality grasslands, 300 hectares would support only 18 head of cattle. Thus, managing the large tracts of ejido land in common was necessary for cattle production. The expropriation of the American-owned Greene latifundio in the summer of 1958 and the subsequent redistribution of the land to local campesinos in early 1959 marked a watershed moment for the establishment of commons land management in the Sonoran borderlands. The invasion of the Greene latifundio has been called the premiere example of peasant invasion of the era and ushered in a final powerful historical era of state-led agrarian reform in Mexico (Sanderson 1981).

Yet agrarismo (the strong agricultural sector), what Sanderson (1981) refers to as the “miracle of the Mexican economy” began to weaken significantly in the 1960s and 1970s. Decades of impressive performance in the agricultural economic sector had hidden fiscal crises in the national economy that were beginning to be undeniable. Decapitalization, growing foreign debt, inflation, and rising unemployment threw the Mexican political economy into turmoil (Sanderson 1981). To counteract these negative trends, state investment in agriculture began to
wane. This period also coincided with the increasing power of private landowners and the agricultural bourgeoisie at the expense of the communal ejido. The stark erosion of power of the agrarian reform sector began in earnest in the early 1980s, when the Mexican economy was marred by the 1982 financial crisis and the devaluation of the peso, followed by a phase of national debt restructuring programs and austerity measures.

In the 1980s, the Mexico Debt Crisis and the devaluation of the peso were accompanied by a phase of national debt restructuring programs and austerity measures. As a result of the 1982 financial crisis the federal government further retracted support for the ejido sector canceling state-sponsored programs, such as price guarantees for staple crops. In 1986, President Miguel de la Madrid signed the General Agreement on Tariffs and Trade (GATT), leading to a reduction in agricultural subsidies by 13% per year. This was also compounded by the slashing of credit to ejido members by the BanRural bank. President Carlos Salinas’s sexenio (1988-1994), further cemented the shift toward a neoliberal understanding of water as an economic good, rather than a public good, and resulted in the reframing of water law to recognize the governance concepts of deregulation, liberalization, and privatization.

In 1991, citing the low productivity of ejido and other communally managed lands, Mexican President Carlos Salinas de Gotari introduced plans to transform the agrarian structure in Mexico, effectively ending a 70-year period of interventionist, state-led agrarian reform. The 1992 introduction of the Programa de Certificacion de Derechos Ejidales (PROCEDE), indicated a major shift in land tenure law and marked the transition to a period of market-led agrarian reform (Perramond 2008). PROCEDE ended the redistribution of land for the creation of new ejidos and fundamentally altered land tenure laws. Previously, ejido land was considered usufruct property, meaning the right was only for the use of the land, not for full ownership. As
such, *ejido* land was inalienable, signifying that the land could not be sold or rented (though scholarship points to widespread illegal renting of land and exchange of titles that occurred). PROCEDE formally initiated the process of legal certification and titling of parcels for privatization, transfer, and sale. On January 1, 1994, the North American Free Trade Agreement (NAFTA) came into force, resulting in the Mexican government dropping protective tariffs and taxes on agrarian goods and a reduction of price supports to producers.

In the early 21st century, *Grupo México*’s control over land and water resources in Sonora and across Mexico, more broadly, has expanded rapidly. Between 2006 and 2012, the Mexican government presented *Grupo México* with more than 600 new mining concessions (100 per year) nationwide. As each concession comes with land territory (and associated water), Germán Larrea, *Grupo México*’s CEO, has become one of the largest land rights holders and speculators in Mexico. In August 2014, the collapse of a tailings dam in the *Buenavista del Cobre* mine, owned and operated by *Grupo México* and located in Cananea at the headwaters of the San Pedro and Río Sonora watersheds caused a spill of 11 million gallons of toxic copper sulfate acid solution, laden with heavy metals, into the Río Sonora watershed, which neighbors the Río San Pedro to the south. Following the spill, officially deemed to be caused by negligence and poor infrastructure maintenance, there have been calls throughout Sonora and in the chambers of Mexico’s Federal Congress to cancel *Grupo México*’s concession to operate the *Buenavista del Cobre* mine. However, the relations of dependence between Grupo México and the Mexican government are extremely strong and entanglements of corruption and distrust run deep. *Grupo Mexico*, a $9 billion corporation with 30 thousand laborers in mines across the Americas, 22 thousand laborers in Mexican mines alone, holds a highly privileged position in the Mexican state. Larrea, the company’s president, is the second richest man in Mexico, with a net worth
estimated at $16 billion. He is an influential member of the Mexican Business Council, founded by his father, an organization that exerts powerful influence over national economic policy and decision-making. And he also serves as advisor to the Mexican Stock Exchange and is a major shareholder of the media company, Grupo Televisa, and Grupo Financero Banamex, the owner of Banamex, Mexico’s second largest bank.

The explosive growth of Cananea’s Buenavista del Cobre mine (Figure 3) over the last two decades has resulted in the mine rapidly expanding its control over the basin’s groundwater resources. Contemporary shifts in the political-economic and ecological conditions in the region have led to a series of acts of enclosure of riparian land, unevenly restricting access for certain types of productive activities, specifically irrigated agriculture and cattle ranching, and crucially, pumping water for the mines and associated urban settlements. In the San Pedro watershed, riparian corridors are highly valued for surface water flows, shallow groundwater, high quality forage for animals, forest resources, and fertile soils (Figure 4).

Though no less dramatic in its impact, the return to exclusive ownership of riparian resources has been signaled by far less pomp and circumstance than the 1959 presidential visit to the San Pedro watershed to transfer the lands of the Greene latifundio to the local campesinos. In the subsequent 50 years, most of the gains made during earlier periods of agrarian reform activism have been severely eroded in favor of private property rights and the expansion of extractive industries. Increasingly riparian zone resources are becoming inaccessible due to a proliferation of fences and security infrastructure to protect mine-owned well fields and the production of water scarcity in downstream communities as a result of the exploitation of the aquifer by the mine, located at the headwaters of the river (Figure 5). Groundwater extraction for the mine’s activities is being experienced in the San Pedro ranching ejidos as reduced surface
water flows, drying of shallow domestic and agricultural wells due to rapid drawdown of the groundwater table, heavy metal pollution of the water, and ecological degradation of the riparian forest. The lack of effective regulation of transnational mining activities harkens back to the lax regulations and exploitation of the environment for capital profit outlined in the mine’s 1903 founding document.

The ongoing enclosure of riparian space represents not only a political-economic shift, but critically, a transformation in socio-ecological relations and practices. The imposition of new borders and boundaries within the riparian zone has been achieved through various legal and policy mechanisms. First, a structural shift toward the privatization of ejido land and its underlying groundwater reserves allows for commons land/state land with community usufructory rights to be parcelized, commercialized, and sold as private property to the mine. Second, through expropriation, the state is allowed to repossess ejido landholdings and redistribute them to mining interests under the constitutional justification of serving the “public good”. Although expropriation and privatization focus on relatively small plots of land, the land is a means to an end: accessing groundwater through very large, deep wells fitted with high power pumps. Although the land area is small, the impacts of the groundwater pumping resonate across the landscape, rippling through social and ecological communities, especially within the riparian corridor zone (Discussed in more detail in Appendix B).

The agrarian reforms of 1992 were accompanied by reforms to the Law of National Waters. The 1917 Constitution of Mexico states in Article 27 that the water is national property and as such its ownership by the Mexican state is inalienable and indisputable. The 1992 Ley de Aguas Nacionales (Law of National Waters, LAN), a response to the debt crisis of the 1980s and ongoing lack of financial capability of the state to invest in infrastructure, was heavily influenced
by the popular discourse of the Dublin Principles and Integrated Water Resources Management (IWRM). Following these neoliberal policy principles, the 1992 law was characterized by the decentralization of water management, a recognition of using free market principles to allocate natural resources, and the commodification of water via the introduction of water rights concessions. These concessions initiated a significant change to water rights law, allowing for the first time for water rights to be rented, sold, and transferred and for water and land rights to be divorced and transferred separately. The LAN also established a national Public Water Rights Registry (REPDA) to record water concession entitlements. In an attempt to decentralize water management and increase participatory governance, the LAN introduced groundwater technical committees (COTAS, acronym in Spanish), river basin councils, user’s associations, and aquifer management councils. In Mexico’s arid and semi-arid zones, such as Sonora, where both demand for water for irrigation and dependence on groundwater extraction from aquifers are high, aquifer management councils were designed to respond to rapid aquifer overexploitation and associated issues with salinization, increasing pumping costs, and poor water quality. It is important to note that although overexploitation of the San Pedro aquifer is a serious problem, no aquifer management councils or groundwater technical committees exist in the watershed.

Following the election of Vicente Fox Quesada to the presidency in 2000, negotiations began to once again reform the LAN. These reforms focused on environmental sustainability and increased decentralization and were meant to respond to dissatisfaction with the 1992 LAN in many communities (Wilder 2010). In practice, the decentralization of Mexico’s national water agency is better described as a deconcentration, as water management remains heavily centralized in Mexico (Wilder 2010). One important aspect of the sustainability focus of the 2004 reforms is the establishment of legislation requiring a groundwater availability report for
each aquifer in the country. The hydrological data published in the official groundwater availability report for the San Pedro aquifer informs the water balance calculations found in this dissertation. According the 2004 LAN reforms, once groundwater extraction exceeds natural aquifer recharge, hence there is no more sustainable availability in the aquifer; no new concessions are to be granted, instead existing concessions are to be traded amongst users. However, I find that in the San Pedro aquifer this has not been the case.

In contrast to the transnational connectivities and imaginary borders that characterized life in the San Pedro River watershed in the 1800s, today borders and boundaries crisscross the basin separating private parcels from tracts of commons land, demarcating mine well fields from ranching and farming land, dividing the headwaters of the river in Mexico from the downstream in the U.S., and establishing the riparian conservation zone on the U.S. portion of the river. However, the re-scripting of new SES relations does not take place on a *tabula rasa* landscape. Instead as Tania Li’s (2007) work reveals, spaces and systems rather than being a clean slate, are imbued with signs and memories, material markers and ephemeral indications. And just as Bijker (2007) informs us that dams and dikes are thick with politics, landscapes too are thick with history, ecology, politics, and memory.

**Research Problem and Context**

Semi-arid regions are faced with the formidable water resources management challenges of meeting multiple, competing demands for limited supply from diverse sectors, including irrigated agriculture, urban centers, and mining and other industrial processes, while simultaneously protecting already diminished in-stream flows and the species — many endangered and threatened — and related ecosystems that depend upon them for survival (Ray et al. 2007). These challenges are further exacerbated by climate regimes exhibiting high seasonal
and short-term variability, tendency to experience long-term drought, and climate change predictions that warn of more variable precipitation patterns and overall increased regional aridity in the future (Barnett et al. 2008; Bates et al. 2008).

Natural resource governance can be defined as “the government’s ability to make and enforce rules, and to deliver services” and encompasses the “range of political, social, economic, and administrative systems that are in place to develop and manage resources” (Global Water Partnership 2003). The Organization for Economic Co-operation and Development (OECD) presents another popular definition of water governance, one that defers emphasis on state government in favor of the role of decision-makers in rule-making practices, processes, and accountability: “Water governance is the set of rules, practices, and processes through which decisions for the management of water resources and services are taken and implemented, and decision-makers are held accountable” (OECD 2016). Worldwide arid and semi-arid areas facing water shortages, including Chile, Mexico and California, have recently implemented market-based water governance reforms that renegotiate existing water property rights regimes. These reforms, characteristic of neoliberal resource management, establish private property rights, introduce market mechanisms into water management, and incorporate environmental externalities through pricing with the expressed goal of using economic logic to redistribute scarce water resources to the most efficient and highest-value uses, with uneven and often contradictory consequences across sectors of water users and for the environment (Bauer 1998, 2004; Bakker, 2005).

Establishing governance structures for the effective and equitable management of transboundary watersheds and ecosystems - hydraulically and/or ecologically connected systems that traverse national boundaries - presents additional difficulties. In transboundary systems, the
flow of water and ecosystem services across political borders produces a tapestry of interwoven, overlapping, and at times contradictory, rules, rights, and resource extraction and conservation practices. The United Nations (UN) Economic Commission for Europe (ECE)’s 2009 publication “Guidance on Water and Adaptation to Climate Change” states that “transboundary water resource management is one of the most important challenges today and in the years to come”, to prevent unilateral and uncoordinated responses that may have counterproductive outcomes, increasing the vulnerability of users and leading to conflict (UNECE 2009: 12). In the US-Mexico border region scholars have found that binational water management is complicated by a number of factors, including: unilateral decision-making, institutional asymmetries, uneven power relations, distrust between actors, uneven access to information, and distinct systems of property relations and natural resource management ideologies (Browning et al. 2004; Wilder et al. 2010; Megdal and Scott 2011; Varady et al. 2013).

Worldwide, riparian corridors – defined as the area from the edge of the stream bank to where an abrupt shift in vegetation type and canopy height occurs – are under mounting pressure from increased water scarcity due to shifting patterns of water availability and consumption. In arid and semi-arid regions, riparian ecosystems are sights of both disproportionately high biodiversity and intensive human activity. These narrow bands of dense forest provide a range of critical environmental services, including freshwater availability, flood protection, nutrient deposition, carbon sequestration, and groundwater recharge. These resource-dense zones support a wide range of economic activities, including ranching, agriculture, mining, recreation, and tourism. In the riparian corridor, biodiversity is critically dependent on hydrologic processes, specifically surface flow, shallow groundwater, and water quality, which are influenced in complex ways by both direct human intervention and broader climatic and landscape-scale

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processes (Scott and Buechler 2013). For example, aquifer depletion, due to excessive groundwater pumping to sustain agriculture and urban areas, reduces the amount and timing of water available to ecological communities in the riparian corridor (Scott et al. 2010).

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

Social-ecological systems (SES) and coupled natural-human (CNH) systems scholarship emerged from the need to develop integrative theory to conceptualize and explain how transformative change occurs in systems characterized by interactions of people and the environment. CNH scholarship posits integrated SES as complex adaptive systems, characterized by uncertainty, surprise, nonlinearity, self-organization, and multi-scalar processes (Holling 1978; Holling and Gunderson 2002; Walker and Salt 2006). With roots in ecology, cybernetics, and system analysis, the complex adaptive system model theorizes the transition of SES through dynamic periods of transformative change (Holling and Gunderson 2002).

This dissertation aims to advance understanding of the coupled social and ecological dynamics that transform riparian forests and the human and non-human communities that depend on riparian resources. The four articles that comprise this dissertation examine the causes and consequences of social-ecological transformations in the riparian zone of the transboundary San
Pedro River watershed, located in the Sonoran Desert borderlands of southern Arizona, USA and northern Sonora, Mexico. The research utilizes an interdisciplinary, mixed methods approach that combines interviews with key informants, including natural resource managers, ranchers, local residents, and political figures, archival research and historical document review, spatial analysis and synthesis of binational datasets, and land use classification and change detection at the watershed scale using methods from remote sensing and geographic information systems.

The objectives motivating this research are twofold.

1. to examine how shifts in social and ecological systems have transformed riparian spaces in the transboundary San Pedro River watershed;
2. to assess the consequences of these riparian transformations for the human and biophysical communities who depend on riparian resources for survival.

Based on these two overarching objectives, there are three interrelated research questions that drive the research and analysis presented in the four chapters of this dissertation (Appendices A - D):

1. How are social-ecological processes at the watershed scale affecting access to water resources in the riparian zone?
2. How are shifting relations of access to water and riparian zone resources influencing and differentiating levels of exposure to hazards over space and across time?
3. Following a disturbance event, how are capacity to respond and recover from disturbance and expectations of accountability shifting over space and across time?

Findings of this research suggest three broad results:

1. Social processes of accumulation of land and water resources by the state and industry (ie. privatization, expropriation, and conservation) are creating uneven spatial and
temporal experiences of water security¹ and insecurity by shifting the amount, timing, and quality of water resources available and who can physically access the riparian zone to derive benefits from riparian resources.

2. Transformations in SES dynamics and access to riparian resources differentially impact exposure to water insecurity (water quality and water quantity) both between and within communities and economic sectors that depend on riparian resources.

3. The ability for local communities and small-scale agricultural producers to cope with increasing water insecurity and respond to disturbance events is decreasing due to limited access of local communities to the wealth produced from natural resource extraction in the region. Further compounding these challenges are shifts at the state and community level toward increasing individuation of responsibility for ensuring livelihood security and a culture of evasion of accountability to remediate ecological degradation within the transnational mining industry.

A central theme of this dissertation is social-ecological transformation. Transformation has been theorized and conceptualized from multiple perspectives, emerging from distinct academic disciplines. Tracing various understandings of transformation, three areas of thought have been key to shaping my analysis and the conclusions that I draw about riparian SES transformation: 1) SES theory and the adaptive cycle model; 2) political ecology, institutions, and the production of risk; and 3) the interrelations of subjectivity, power, and environmental governance. In particular, two models of SES transformation inform my understanding of how complex adaptive systems experience change, navigate through and manage periods of

¹ I define water security as: access to adequate quantities of water of acceptable quality to support livelihoods and sustainable production to ensure resilient human and ecological communities. For an in depth review of the term water security and the genealogy of its definition see the discussion in Appendix
transition, and retain or lose their functionality. The panarchy model (Figure 6) proposed by Holling and Gunderson (2002) posits an adaptive cycle consisting of four phases of transformation (exploitation, conservation, release, and reorganization). Over time, SES transition through these stages experiencing different levels of system and sub-system functionality; each phase is characterized by distinct relations among the system variables. At different points in the transformative cycle, the system components are theorized to be more or less sensitive to external shocks and disturbance based on degree of connectedness, thus impacting the resilience of the system and the capacity to manage and adapt to changing conditions (Holling and Gunderson 2002). A second, complimentary model of SES transformation introduced by institutional theorist Elinor Ostrom (2009) theorizes complex SES as composed of eight, interrelated core subsystems (social setting; ecosystem setting; resource units; resource systems; governance system; users; interactions; and outcomes). This model is useful because each subsystem can be decomposed into second- and third-level variables of increasing level of detail. Ostrom’s framework provides a structure to identify and analyze the case-specific variables of the SES, a drawback in Holling and Gunderson’s model, which focuses more on the transition of the SES through the phases of the adaptive cycle and less on the specific components and sub-components of the system. For more detail, see the Literature Review section that follows.

This dissertation takes inspiration from various fields of thought and aims to integrate bodies of scholarship, while recognizing that tensions arise from this type of conceptual integration. For example, throughout the dissertation the articles grapple with the tension of following a Marxist political ecology approach or the more recent ‘new materialism’ turn in geography and philosophy. In a helpful analogy, Banister (2014) describes the shift from a
Marxist approach to a new materialist approach as a move from understanding hydrosocial dynamics as “metabolism” (digestive system) to “always in the making” (connective tissue). The move toward an understanding of hydrosocial dynamics through the connective tissue model serves to strengthen the emphasis on process and connection and the mobility and mutability of objects within the analytic framework (Banister 2014). Where a Marxist approach understands the transformation of nature as a product of shifting production regimes, changes in human labor, and processes of capitalist commodification, the new materialist approach conceptualizes the world through an immanentist ontology that argues for an understanding of fluidity and flow, rather than fixity, and is sensitive to the connectivities, flows, and interdependencies that draw humans, biophysical systems, and non-living objects into relation (Meehan et al. 2013; Meehan 2014; Meehan et al. 2014; Banister 2014; Madrid-López and Giampietro 2015; Steinberg and Peters 2015).

Literature Review

The Adaptive Cycle: Theorizing Transformation in Social-Ecological Systems

A robust literature attends to the conceptualization of SES, drawing from diverse theoretical and empirical traditions, including Elinor Ostrom’s well-known institutional analysis, coupled natural and human (CNH) systems’ framework of complex adaptive systems, and critical approaches from political ecology. In the institutional theory scholarship, the SES framework emerges from a rich body of empirical case studies of common pool resource (CPR) management in ecosystems and communities across the globe. Rather than imposing a false separation of natural and social components in a system, the SES framework recognizes that these components constitute a single system, characterized by feedbacks between the
environment and society across multiple temporal and spatial scales. Elinor Ostrom defines SES as “composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc” (Ostrom 2009: 419). Central to understanding the ever-shifting interactions among institutions and the environmental conditions in which they operate are the concepts of adaptation, transformation, and resilience. These concepts provide a bridge between the institutional theory literature and the coupled human and natural systems scholarship, which presents a distinct, yet interrelated, understanding of SES.

The looping figure-eight panarchy heuristic, first presented by Holling and Gunderson (2002), presents a model of how complex systems transition through dynamic change. This adaptive cycle model, defined by three properties – potential for change, connectedness, and resilience – describes the behavior of SES over time as they progress through four specific phases: exploitation (or growth), conservation, release, and reorganization (Figure 6). However, each adaptive cycle comprises only one part of the larger theory of socio-ecological change, known as panarchy. The meta-level panarchy model theorizes each individual adaptive cycle as embedded in nested sets of additional adaptive cycles occurring at multiple spatial and temporal scales.

Each adaptive cycle within the panarchy contains a front loop and a back loop. The front loop is characterized by slow incremental change during the transition between the exploitation and conservation phases, a period of growth and accumulation with relatively predictable dynamics. In contrast, the back loop is a period of rapid transformation that occurs as the SES transitions from the release phase into the reorganization phase, a period marked by heightened uncertainty, innovation, and experimentation. The transition between the front loop and the back
loop is triggered by a disturbance event. Unable to withstand the disturbance and maintain its current configuration, the system experiences a process of creative destruction.

The transition from the release phase to the reorganization phase of the adaptive cycle (or, the backloop), a period marked by novel recombinations, allows “the previously accumulated mutations, inventions, external invaders, and capital [to] become resorted into novel combinations, some of which nucleate new opportunity” (Holling 2001: 395). This transition is posited to release previously accumulated resources from the rigid, over-connected relations in which they had been tightly bound during the conservation phase, allowing actors to harness the newly liberated flows of energy and capital (Westley et al. 2013). The reorganization phase, which follows the release, exhibits significantly heightened uncertainty, but may also be “wonderfully unpredictable” (Holling and Gunderson 2002: 46), representing a period of restructuring of relations and redistribution of resources under conditions of high flexibility. Transformative potential exists in the turbulent back loop phase of the release and reorganization stages of the adaptive cycle. The loss of capital following the transition from the conservation to the release phase requires recruitment, capture, and redistribution to occur as the system moves rapidly from the release stage to the reorganization stage (Goulden et al. 2013). The role of novelty, creativity, and mutation is central to SES transformation in panarchy theory, yet the theorization of how to take advantage of revolutionary, yet “transient windows of opportunity” (Holling 2001: 397) remains underdeveloped. The formation of previously unimaginable solidarities and political possibilities is present in the theoretical panarchy model, but never convincingly animated in practice.

Social-ecological resilience, one of the three fundamental properties of the adaptive cycle model, is defined as the magnitude of shock (or amount of disturbance) that the system can
absorb while maintaining its current structure and composition, hence not transitioning to an alternative system state (Holling and Gunderson 2002). Resilience is not theorized as a spatially or temporally fixed quantity across the system, but instead is posited to expand and contract as the SES transitions through the four different phases of the adaptive cycle. Although resilience represents only one property of the adaptive cycle model, over the last decade it has come to define this theoretical approach, often termed, resilience thinking (Walker and Salt 2006). Globally, the influence of resilience thinking has infiltrated environmental policy and governance through the diffusion and implementation of adaptive management (Engle et al. 2011).

Transformative potential exists in the adaptive cycle phases of release and reorganization, yet nuanced understanding of how transformative events affect the capacities of subjects to facilitate, strategize for, manage, or resist turbulent change remains limited. Westley et al. (2013) introduce a theory of transformative agency that links agent strategies with phases of system change in the adaptive cycle model. Agents who best anticipate and prepare for disturbance and tailor their actions to the specific characteristics and opportunities of each adaptive cycle phase are most likely to successfully mobilize resources and take advantage of emerging political possibilities. Yet, the authors do not adequately explain why certain subjects are more likely to be change agents than others, prompting the critique that resilience theorists tend to focus too narrowly on the role of the most powerful actors in the system to effect transformational change (Nelson 2014). Recent scholarship characterizes the resilient subject as: entrepreneurial, flexible, adaptive and innovative; proactive in seeking out, adapting to, and exploiting situations of uncertainty to his or her advantage; and able to behave as an informed decision-maker (O’Malley 2010; Joseph 2013). Rather than being posited as traits that people either do or not possess, the
traits of the resilient subject involve “behaviors, thoughts, and actions that can be learned and developed in anyone” (O’Malley 2010: 498).

Successful management of complex SES is characterized by the ability of adaptive managers to confront multiple uncertainties (Walker and Abel 2002) through a scientific approach to management based on hypothesis generation, monitoring and data collection, and experimentation (Westley 2002). An adaptive manager archetype emerges from resilience thinking as someone who performs certain distinct roles to correctly manage himself and his environment in the context of uncertainty and surprise. More specifically, Westley (2002) describes the adaptive manager as comprising the following characteristics: strong values; love of science; aptitude for being a scientist, collaborator, politician, and manager; and strong control of emotions, little fear of conflict, and great humility. Problematically, traditional resilience thinking naturalizes the emergence of the adaptive manager without critical engagement of how and why this subject has come to exist. The adaptive manager is presented with little critical interrogation, as a category that exists beyond politics, although the production of the subjectivity is intensely political. Casting forth the adaptive manager as the correct form of conduct of the self in relation to the environment serves to homogenize difference, eliding diversity, multiplicity and differentiation, while implicitly suggesting that each individual is able to, and should aspire to, become an adaptive manager.

Although resilience theory and the adaptive capacity model are widely used in ecological research and have been gaining traction in social science research, scholars continue to be critical of the ability of these models to adequately engage with and incorporate fundamental aspects of social systems, including human agency (Adger 2000), the political-economy of natural resource control, exploitation, and dispossession (Davidson 2010; Michon 2011; Pelling and Navarrete
2011; Robards et al. 2011; Cote and Nightingale 2012), the operation of power (Phelan et al. 2013), and the production of social divisions and inequalities (Mackinnon and Derickson 2012). The panarchy conceptualization of SES transformation draws on findings in biological and ecological science to hypothesize system dynamics. When a system crosses a threshold, defined as a critical juncture of crisis, collapse, and reorganization (Holling and Gunderson 2002), ecosystem processes allow species to recruit resources released through the collapse. These ecological dynamics are translated and coded onto social and institutional systems, imagining the socio-political response during the reorganization phase as analogous to the ecological response. The underdevelopment of the “social”, particularly social theory, in resilience-based social-ecological systems thinking, which tends to apply hypotheses and findings derived from experiments in ecology, is a significant drawback of the adaptive cycle model. Casting social systems into the ecological terms encompassed by the resilience framework, is also problematic because social systems have the ability to purposefully postpone the effects of ecological disruption in space and time (Davidson 2010).

Resilience theory has also been subject to substantial criticism for its role in a wider restructuring of social-ecological relations under neoliberalism (Grove 2013a, 2013b, 2014). Neoliberalism is a specific form of social rule that institutionalizes a rationality of competition, enterprise, and individualized responsibility. In *A Brief History of Neoliberalism*, David Harvey defines neoliberalism as “a theory of political economic practices that proposes that human well-being can best be advanced by liberating individual entrepreneurial freedoms and skills within an institutional framework characterized by strong private property rights, free markets, and free trade” (Harvey 2005: 2). Critics argue that through its articulation with neoliberalism, resilience theory has become linked with an ideology that privileges individualized, market-based solutions
over collective political solutions (Brown 2006), valorizes self-reliance and responsibility (O’Malley 2010), favors discourses of competitiveness, securitization, devolution, and the need to promote economic growth (Walker and Cooper 2011; Joseph 2013), and reinforces the ideal of the fundamentally self-interested individual (Read 2009). A flourish of recent analyses tracing the genealogy of resilience theory (O’Malley 2010; Walker and Cooper 2011; Mackinnon and Derickson 2012; Joseph 2013; Nelson 2014) reveal, however, that rather than being a necessary and immutable relation, the bind between resilience and neoliberalism is historically contingent. In excavating this relationship, these investigations demonstrate that resilience theory is vulnerable to neoliberal co-optation due to the its lack of an internal political economy critique (Nelson 2014) and its naïve importation and subsequent extension of naturalistic concepts and metaphors from the ecological sciences to provide natural law-like descriptions of complex social relations (Mackinnon and Derickson 2012). However, by historicizing the emergence and development of resilience theory to make visible how, when, and under what historical and geographical conditions the now familiar suturing between resilience and neoliberalism occurred, it becomes possible, following Nelson (2014), to identify fracture lines and exploit weaknesses in this relation. Thus the possibility exists to re-appropriate resilience thinking for progressive and more equitable ends.

Recognizing these inadequacies of the traditional adaptive cycle model to capture the full range of dynamics of riparian transformation, in the following literature review sections, I draw on insights from political ecology, critical risk theory, and social theory to highlight other theoretical and conceptual frameworks that help to illuminate the complex interrelations between political, economic, cultural, and ecological systems, and the role of subjectivity in mediating experiences of SES transformation. Scholarship from these bodies of knowledge demonstrate the
importance of understanding how relations between natural resources and power intersect to shape differential outcomes among diverse social groups, producing uneven topographies of access to natural resources within and between communities (Swyngedouw 1999; Birkenholtz 2009, 2013; Bakker 2010; Sultana 2012, 2013; Budds and Sultana 2013). Rather than being natural occurrences, conditions of insecurity are recognized as products of social relations and processes. The description of the transition of the system through the phases of the adaptive cycle offered above hints at, but does not robustly interrogate, the larger structural issues underlying transformations to undesirable system conditions, such as aquifer depletion and associated crises of water scarcity. Thus, I hope to animate a more equitable and progressive conceptualization of SES transformation beyond the panarchy model.

**Political Ecology, Institutions, and the Production of Risk**

Critical theory approaches from political ecology, institutional theory, and critical risk studies provide analytical capacity and explanatory power for examining both the drivers and consequences of social-ecological transformation. Across these bodies of scholarship exist a common interest in understanding how relations of power, property, access to resources, and control over the means of production influence human behavior, systems of natural resource management, and capacity to adapt to changing political-economic and environmental conditions. Furthermore, these traditions share an engagement with analyzing how shifting arrangements of access to and control over resources, especially through the persistent penetration of capitalist relations of production into nature, produce implications for livelihoods, equity, social relations, and ecological change.
As an analytical framework, political ecology is useful for interrogating governance failures and unintended consequences as it is sensitive to the dynamics of differing forms of, and conflicts over, accumulation, property rights, and disposition of surplus (Peet and Watts 1996; Watts 2000; Mann 2008; Robbins 2012). In particular, the lens of political ecology aims to challenge accounts of environmental crisis that uncritically situate the driving forces of degradation in population growth, culture, or poor land-use practice (Watts 2000). Rather, political ecology focuses attention on modes of production that generate exploitative relations and the accumulation of surplus value and wasteful consumption patterns for some at the expense of others, often the very groups maligned for environmental degradation in non-critical analyses of human-environment relations. Moreover, political ecology opens the possibility to seriously examine river representations and discourses and how these shape policy and practice, including why, how, and when cultural practices are contested, fought over, and negotiated (Watts 2000), contributing to an explicitly political understanding of human-environment relations.

Robbins (2012) outlines a research agenda that calls for diagnosing specific political and ecological drivers that regulate change, keeping at the forefront the intimate link among marginalization, resistance, and ecological change. In a seminal text, Blaikie and Brookfield (1987: 14) pose the question, “why have land management failures occurred?” Their analysis and numerous following studies, have cemented political ecology as a useful lens through which to study governance failure, as it marries the concerns of ecology and critical political economy of the environment, aiming to support and advance the view that environmental problems are at their core social. Utilizing social constructionist and postmodernist approaches, political ecology

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2 Karen Bakker (2010) defines governance failure as occurring when “there is a mismatch in decision making between citizenship and associated political rights, on the one hand, and institutional and cultural practices on the other” (45).
problematizes, challenges, and resists dominant worldviews of the environment and resource use. Thus, viewed through a political ecology lens, land use decisions are understood as never apolitical, but instead recognized for always resulting in social and environmental changes whose material outcomes produce winners and losers, favoring certain groups over others (Hecht 1985).

Political ecology is a powerful framework because it consciously “works to ‘denaturalize’ certain social and environmental conditions, showing them to be the contingent outcomes of power, and not inevitable” (Robbins 2012: 12). Political ecology’s emphasis on interrogating the material relations of production, specifically questions of access to and control over resources, extraction and distribution of surplus value, and the accumulation and distribution of positive and negative outcomes is rooted in a Marxist conception of historical materialism (Mann 2008). Rather than mystifying and eliding systems of socio-natural relations, the historical materialist approach is useful because it provides a methodology to elucidate historical processes and illuminate stages of development that have led to the present situation (Hobsbawm 1962).

Central to the historical materialist argument is the struggle for control of production, thus questions of labor are inextricably linked to questions of land. Through this linkage of labor and land, it becomes evident that shifts in property regimes that rescript relations of land ownership also serve to shift control over the means of production, serving to reorganize labor relations and to expand or limit use rights over land, water, and other natural resources, thus producing winners and losers. Ribot and Peluso demonstrate that property rights are explicitly political. They argue “the ability to benefit from resources is mediated by constraints established by the specific political-economic and cultural frames within which access to resources is
sought” (Ribot and Peluso 2003: 164). Sikor and Lund go a step further linking property, legitimacy, and authority, as “property is only property if socially legitimate institutions sanction it” (2009: 1). This legitimacy must be actively established and continually (re)established through negotiation as people and institutions are positioned differently in relation to resources at various historical moments, thus what is considered legitimate property is historically contingent (Sikor and Lund 2009). Therefore, relations of access (defined as the ability to derive benefits from things (Ribot and Peluso 2003) are dynamic and always changing based on a group’s position and power within various social relationships at multiple scales.

Attention to institutions is also critical as institutions serve to link human-environment systems, and shape human behaviors and practices of natural resource extraction, consumption, and disposal with implications for collective decision-making, cooperation, and conflict. Although political ecologists focus on institutions, the school of institutional analysis, often traced to foundational texts by Elinor Ostrom (1990) and Douglass North (1991), offers key contributions to identifying and understanding variables that encourage or inhibit individuals to cooperate and coordinate their behavior to manage local resources collectively. Following a distillation of the contributions of institutional analysis by Blomquist et al. (2010), my dissertation is deeply informed by the following key findings from the institutional analysis literature: 1) asymmetries of power, information, and resources exist among and between local actor groups; 2) differences among the actors whose behavior is being coordinated or whose cooperation is needed must be recognized and reconciled; 3) previous interactions between actors influence future interactions; 4) the extent of autonomy and sovereignty of actors to develop new rules and to modify existing institutional arrangements is positively correlated with
the acceptance and implementation of new rules for natural resource management; and social norms of trust and expectations of reciprocity play critical roles in organizing collective action.

Although political ecology is useful for its ability to reveal the “failures,” unintended consequences, contradictions, paradoxes, and perverse outcomes of natural resource management schemes, a drawback of this body of scholarship it is that it lacks a significant engagement with critical theories of risk. Critical risk theorists (Beck 1994; Dean 1999; Bulkeley 2001; Stanley 2013) have advanced risk theory by introducing a relational theory of power (Foucault 1980) and by revealing how risk operates as a knowledge practice and logic of management (Dean 1999). Stanley (2013: 13) warns that managing uncertainty through risk serves to “tell the story of a flat geography,” one that “observes the way uneven geographies are produced and exploited,” while simultaneously constructing certain spaces and bodies as receptacles for the containment of the negative effects that accompany capital accumulation. A central insight drawn from critical risk scholarship is that it is through differential exposure to risk that certain actors’ access to resources can be secured, while for others’ access is reduced or denied altogether.

The commodification of nature - defined as the penetration of capitalist relations of production into nature - a theme central to the scholarships of both political ecology and critical risk studies presents one productive avenue for theorizing the production of unequal risk in contemporary environmental politics. Although Karen Bakker (2004, 2005) reminds us that water is an especially ‘uncooperative commodity’ due to its unique geographical, socio-cultural, and biophysical properties that violate the conditions of standardization and interchangeability necessary for well-functioning markets, pressures to exchange units of water through market mechanisms are on the rise. The result of processes to commodify natural resources are
transformations of SES relations which create situations where certain actors become
beneficiaries of risk, while others become bearers of risk.

For many risk theorists, the politics of environmental risk are intimately interrelated with
global capitalism, governmentality, and the production and distribution of knowledge (Beck
“risk society” thesis, is based on the seemingly paradoxical idea that the victories of capitalism
and modernity (i.e. technological progress, science, and industrialism) are in fact contributing to
increased risk, rather than diminishing risk (Beck 1994; Jarvis 2008). Beck argues that processes
of globalization, such as transnational trade partnerships, serve to compromise the legitimacy and
accountability of the state. As markets are de-nationalized, states are forced to respond to an
international constituency of banks, development agencies, and foreign direct investments rather
than to their domestic constituency of citizens.

Accompanying the emergence of the risk society is a situation in which “the social,
political, economic, and individual risks increasingly tend to escape the institutions for
monitoring and protection in industrial society” (Beck 1994: 5, emphasis added). Risk is
increasingly individuated while simultaneously the overall exposure of individuals and society to
risk increases. The transition to reflexive modernization also means that instead of distributing
wealth (‘goods’) through society, institutions become tasked with distributing socially produced
‘bads,’ provoking conflict over the construction and contestation of obligation and responsibility
(Bulkeley 2001). Making this point, Beck (1994:7) writes that people once are released into the
“turbulence of the global risk society…. [they] are expected to live with a broad variety of
different, mutually contradictory, global and personal risks.”
An additional critique of political ecology that is salient for this dissertation is the limited focus on the interrelations among environmental governance, the production of subjectivity, and identity politics. Recognizing this gap, feminist political ecologists (Rocheleau 1995; Sundberg 2004; Li 2007; Elmhirst 2011; Guthman 2011; Mollet and Faria 2013; Carney 2014) and Arun Agrawal’s (2005) foundational text, *Environmentality*, have made strides to integrate insights from cultural and political geography and social theory to close this gap. In particular, cultural geography lends its focus on theorizing corporeal experience and differentiation, while political geography attends to the complex and intricate relationship that is constantly under negotiation between the subject and the state producing particular subjectivities under particular modes of governance. In the next section of this literature review, I argue that an integrated theory of SES transformation must recognize the production of subjectivity and attend to identifying the ways that subjectivity and environmental governance regimes are entangled through the operation of power.

**Subjectivity, Power, and Environmental Governance**

Subjectivity, the condition of being a subject who possesses perspectives, experiences, feelings, beliefs, and desires (Mansfield 2000), is an integral component within social, political, and cultural transformations. Subjects not only manage transformative events, but transformations in social-ecological relations also serve to shape and reshape subjectivity. Power is essential to subjectification, the process through which individuals come to be constituted as subjects (Foucault 1986). Subjectivity both shapes and is shaped by dominant social, cultural, political, and ecological relations (Mansfield 2000), and is constituted within diffuse and circulating relations of power, where subjects exist in relation to other people, institutions,
practices, the state, ecologies, and landscapes (Foucault 1980; Agrawal 2005). It is within these relations that the subject is produced through and governed by myriad force relations; relations of power that serve to subjugate and differentiate through governance techniques that compare, contrast, and hierarchize individuals. Attending to the relations through which subjectivities are produced and certain subjectivities come to be privileged can further advance understanding of the role of agency during periods of transformative change.

In *Environmentality*, Arun Agrawal uses insights from Foucault to interrogate the relationship between changes in the technologies employed by the state to govern the environment and related shifts in environmental practices and beliefs that are productive of new subjectivities. For Agrawal, the term ‘environmentality’ (a play on Michel Foucault’s ‘governmentality’) refers to the knowledges, politics, institutions, and subjectivities that become articulated under new formulations of environmental management and regulation. New regulations and management regimes require new subjectivities to accept and perform a new set of relations with the natural environment. Agrawal contends “the goal is to understand and describe how modern forms of power and regulation achieve their full effects not by forcing people toward state-mandated goals but by turning them into accomplices” (2005: 216-217).

Borrowing from Foucault, Agrawal argues that power does not only operate negatively, by constraining actions, rather, power operates positively to produce subjects who produce and reproduce the types of activities that are desired.

Following Michel Foucault (1986, 1994), it is necessary to interrogate the micro-processes and everyday practices and experiences through which power operates and domination, difference, and resistance are produced and maintained. It is through the articulations of these webs and flows of power and the everyday encounters between the state
and subjects, both real and imagined, that repressive or progressive state-subject relationships are experienced. As a point of departure, Agrawal (2005) argues that a focus on the technologies of government encourages attention to the processes through which these concepts are consolidated and naturalized. Thus by focusing on the technologies of government employed in a specific moment, it becomes possible to interrogate how the current assemblage of interdependent elements, including subjectivity, conceptions of nature, and the management of populations, come to seem natural and eternal, rather than contingent and fleeting. Although these elements may appear static, secure, and cohesive, the constellation of elements is constantly in motion and always in-the-making.

The production and reproduction of subjectivity vis-a-vis the state and environmental governance is a central piece of the conceptual framework of environmentality, yet Agrawal (2005) notes that the political ecology toolkit, though attendant to analyses of politics and institutions, severely lacks a nuanced understanding of the role that subjectivity and knowledge about the environment play in ecological practice and in the production of new environmental subjects. Here, scholarship from identity studies and feminist bodies of thought is helpful for proposing a more robust understanding of subjectivity that could be useful for theorizing transformative moments in social and ecological relations. Tania Li (2000) drawing on Stuart Hall’s concept of articulation - the double process of rendering a collective identity, position, or set of interests explicit, and of conjoining that position to define political subjects - contends that articulation is a useful lens for understanding identities as always becoming. Li’s work illustrates that identities emerge through discursive representation, imagination, and corporeal materiality. Informed by the feminist scholarship of Judith Butler (2004) and Elizabeth Grosz (1994), this view of identity construction as always in-the-making calls for increased attention to corporeality
and the body as a site of social contestation. In this framework, the body is understood as a cultural construct, contingent on history and geography, and constantly undergoing a process of production. Longhurst (2001) suggests that bodies be understood not only as effects of discipline and power but also as active agents in the production and operation of power. The body, a key material site of social production and reproduction, is recognized as an expression of social inscriptions. The body is also the corporeal structure that grounds the ways in which the everyday, material conditions of life are experienced. Rather than being fixed with one permanent identity, the body instead is a space in which discourse is performed or resisted through material action. Identities are continuously shaping and being shaped by power relations, history, and culture. In an analysis of human-animal relations, Hovorka (2012) demonstrates that subjectivities are co-constructed between humans and non-human animals based on material realities and daily relationships, and evolve with changes in markets, agricultural practices, and land dynamics. Thus there exists a link between subjectivity and agrarian production regimes.

The framing of SES problems and phenomena impacts the types of responses possible, eliciting different political responses depending on whether subjects are positioned in relation to natural and incontestable environmental changes or malleable, mitigable ones (Cameron et al. 2015). In northern Sonora, the positionality of subjects vis-a-vis control over capital and natural resources is salient to experiences of SES transformation. For example, to overcome barriers to expanded production and capital accumulation, such as water scarcity, the mining sector in northern Sonora depends on the uneven production of difference and the marginality of the ejido communities. It is through the production and exploitation of difference that new land and water resources can be discursively framed as available for exploitation (Stanley 2013). An additional
process of SES transformation examined in this dissertation is the establishment of structural conditions, which are conducive to producing neoliberal subject positions. Thus, subjects who conform to neoliberal modes of thinking, knowing, and managing riparian spaces and riparian relations are better positioned to navigate changing social-ecological relations in the riparian zone with increased security and reduced vulnerability (See Appendix A).

In the final section of this literature review, I present emerging lines of thought in human-environment geography that recognize solidarities and shared experiences between humans and the non-human world to propose a new riparian ethic that prioritizes life over profit and is sensitive to the possibility of collective action based on commonalities and ways of being together that do not reduce the interrelations between humans and the non-human world to the logic of the commodity.

*Toward a Radical Riparian Ethic*

Human-environment geographers and political ecologists have made contributions to the scholarship on ethics, pushing this work in new directions to attend to the commitments and solidarities that form the basis of an ethics that explicitly recognizes the non-human and our inescapable entanglements with the non-human world. While some scholars call for the development of an ethic of human solidarity that transcends social divisions and instead recognizes commonality in the human experience (Linebaugh 2014: 140), post-humanist inspired scholars, such as Bruce Braun (2002), draw attention to the need for an environmental ethic grounded in the inescapable entanglement of human and nonhuman bodies and objects. Following the materialist (re)turn (new materialisms) in geography and the social sciences, Whatmore (2006) dares us to reanimate more-than-human matter and to focus renewed attention
to bodily engagements across species. Redefining landscapes as “co-fabricated between more-than-human bodies and a lively earth” (Whatmore 2006), the co-constitution of human and non-humanity via a sticky web of connections (Bennett 2004) comes into focus. Drawing our attention to the relations of turbulence, collision, evolution, solidification, and disintegration that animate the encounters between human and non-human, Bennett (2010) argues that decency and a decent politics are fostered if we tune in to the strange logic of turbulence (p. xi, emphasis added). She refers to events within the “turbulent immanent field” as “encounters between ontologically diverse actants, some human, some not, though all thoroughly material” (Bennett 2010: xi). It is through sensuous enchantment with the diverse materialisms of the everyday world, she argues, that may spark the practice of ethical behaviors.

More recently, Collard et al. (2015: 253) propose a rethinking of conservation to focus on multi-species abundance—“a world literally filled to the brim with different creatures”—which is based on an ethic of more diverse and autonomous ways of living together among multiple forms of life. In addition to the reconceptualization of abundance as an ethic for living together in the Anthropocene, Derickson and MacKinnon (2015) introduce a politics of resourcefulness that insists on making visible and “sayable” marginalized and previously invisible imaginaries for progressive transformative possibilities that do not conform to current neoliberal agendas. Corporeality, thus, is no longer attentive only to human bodies, but instead becomes an intimate fabric woven through all the bodies that compose the ‘livingness’ of the more-than-human world (Whatmore 2006). This expansion of subjectivity to include attentiveness to more-than-human forces simultaneously expands the categories of vulnerability, justice, and resilience to the other-than-humans who inhabit and co-constitute riparian spaces.

A conscious shift toward recognizing these solidarities in practice informs the very basis
for a radical ‘riparian ethic’ that aims to break the traditional boundaries of social-ecological management in favor of novel (re)animations of a multiplicity of bodies and forces that compose riparian worlds. The hegemonic influence of the ‘logic of the commodity’, which is all too often the ethic that animates riparian spaces, may be thwarted by rendering visible and sayable the social and ecological processes that shape transformations in material conditions. Bruce Braun (2002) draws on the concept of dwelling to compel a new ethic of solidarity. He writes, “if we listen attentively, and critically, we can locate affinities, build coalitions, and imagine other, better ways of being together that do not reduce all of nature, and all of culture, to the logic of the commodity” (Braun 2002: 6).

Thus, a riparian ethic animated on materialist grounds draws our attention to the capabilities and potentialities of all objects and forces, allowing us to dwell on and in riparian worlds that are co-fabricated by and through human and more-than-human, localized and extra-local, forces. It calls on us to re-politicize understandings of the social and ecological struggles that accompany transformative moments in human-environment relations, recognizing that processes of imagining and enacting new social-ecological futures are deeply political. As part of this project, there is value in tracing popular conceptual frameworks, such as social-ecological resilience theory, to their origin to rediscover the radical and revolutionary imaginaries on which their emergence was predicated. Much of the body of scholarly literature and on-the-ground management approaches to arise from resilience thinking oppose the production of radical imaginaries and the implementation of transformative potential toward progressive alternative political futures. Yet, I argue returning resilience thinking to the adaptive cycle model (ie. panarchy) elucidates the politics of social-ecological transformation, revealing the differentiated experiences of distinct human and more-than-human bodies following transformative events. It is
possible (and necessary) to rescue the radical political potential offered by panarchy.

I argue that a return to thinking about ethics provides new ways to imagine reconciling conflicting interests and reviving strategies of collective resource management. Rather than eliding and ignoring social and ecological difference, it is imperative to recognize and value the multiple perspectives, interests, and knowledges present in riparian zones. In contrast to laws, policies, and practices that manage through externally imposed enclosure and exclusion, I argue that emphasizing management approaches based in a democratic, inclusive environmental ethic may trigger the emergence of new political possibilities. Approaching the interconnections between diverse human communities and the multiple nonhuman entities that exist in riparian systems as webs of intricate relations, impossible to disentangle, it becomes possible to locate affinities, cultivate solidarity, and build coalitions across social and ecological boundaries. Critically, we must redefine the interface between the social and ecological worlds and contemplate why and transform how these boundaries are maintained. An approach based on coalitions and cooperation creates opportunities to move beyond contentious narratives and assignations of blame toward management decisions grounded in collective responsibility. Furthermore, instead of dedicating attention solely to economic growth, which favors unsustainable industrial-scale mining and agriculture with little regulation, a social-ecological approach sensitive to a post-humanist ethical approach may take seriously broader social and environmental considerations, including social reproduction and health and well-being for both human and non-human communities.
Explanation of the Dissertation Format

This dissertation is comprised of four stand-alone articles. The first article, *Shifting Topographies of Water Security in the US-Mexico Borderlands: A Social-Ecological Systems Conceptual Framework* (Appendix A), co-written with Dr. Christopher Scott, assesses different experiences of water security in the Sonoran-portion of the watershed across two livelihood categories, agriculture and ranching, as groundwater concessions are consolidated under the control of the *Buenavista del Cobre* mine. The article is written for submission to *Water Alternatives*.

The second article, *Social-Ecological Transformations in Riparian Zones: The Production of Spaces of Exclusion and the Uneven Development of Resilience in the Sonoran Borderlands* (Appendix B), identifies three political-economic mechanisms that are serving to enclose the riparian zone of the binational San Pedro River watershed leading to landscapes of exclusion for agrarian producers. The paper has been accepted for publication as a chapter in the edited volume *Between the Lines: The Social Ecology of Border Landscapes* (Eds. A. Grichting and M. Zebich-Knos). The paper was also awarded the 2016 Best Student Paper Award by the Cultural and Political Ecology specialty group of the American Association of Geographers.

The third article co-written with Maribel Pallanez of the Colegio de Sonora and Dr. Christopher Scott of the University of Arizona, *Uneven Conservation of Binational Riparian Resources: Institutional Conflict, Ecological Uncertainty, and Community Organization* (Appendix C) provides comparative institutional analysis, based on Elinor Ostrom’s SES Framework, to characterize two attempts, one successful and one not, to establish riparian conservation areas along the San Pedro River. The article is written for submission to the journal *Society and Natural Resources*. 
The fourth article co-written with David Chan a colleague from the University of Arizona School of Natural Resources and the Environment, *Developing a 2010 Land Cover Classification for the Upper San Pedro River Watershed: A Classification and Regression Tree (CART) Model Approach* (Appendix D), presents the methodology and results of a land cover classification and change detection analysis for the binational watershed based on 30 meter resolution NASA Landsat imagery for the year 2010. The article written for submission to the *International Journal of Remote Sensing*. The paper was the recipient of the Central Arizona Project (CAP) Award for Water Research, 2nd Place Graduate Student Paper Competition

**PRESENT STUDY**

**Study Site**

The transboundary San Pedro River originates in northern Sonora, Mexico and flows north into the United States through Arizona where it meets the Gila River, which eventually flows into the Colorado River. The watershed covers 1,875 square miles encompassing diverse and ecologically sensitive ecosystems, varied topography, and an eclectic mix of populations, ranging from the urban centers of Sierra Vista, AZ and Cananea, MX to the military base, Fort Huachuca, to the rural populations of cattle ranchers and small-scale agricultural producers, and the massive *Buenavista del Cobre* copper mine.

The San Pedro River riparian corridor has been simultaneously a site of intensive grazing and agriculture and a critically important area for biodiversity conservation, providing unique forested and aquatic habitat for 84 mammal species, 14 fish species, and over 250 migratory bird species. As a response to environmental degradation in the riparian corridor due to groundwater exploitation and urban development in southern Arizona during the 1970s and 1980s, in 1988 the
US Congress federally designated a 40-mile riparian conservation area, known as the San Pedro Riparian National Conservation Area (SPRNCA). Across the basin, highly variable precipitation combined with irrigated agriculture, rapid population growth, and limited access to surface water has led to steadily increasing groundwater withdrawals that currently exceed the natural rate of recharge. In semi-arid landscapes, rivers are among the most susceptible to fluctuations in water availability due to seasonal variability in precipitation, increases in water extraction, and changes in the seasonality of flows due to both short- and long-term climate factors (Adamson et al. 2009; Cunningham et al. 2009; Potter and Chiew 2011). Within the United States portion of the basin groundwater pumping has caused the San Pedro River to lose over half of its historical perennial surface water flow, a condition aggravated by high well densities in close proximity to the river.

The two climate variables that most significantly impact the variability of water availability are precipitation and evaporation. In semi-arid and arid climates potential evaporation (the amount of water that would hypothetically evaporate from an open water source) is greater than or equal to average annual precipitation, which has implications for water availability and storage. In settings where potential evapotranspiration (the sum of evaporation and transpiration from plants) is greater or equal to precipitation, surface water is likely to be evaporated or transpired within a short period after rainfall (Letcher and Powell 2008). The Upper San Pedro River basin receives an average of 300 to 750 millimeters of precipitation per year based on location within the basin.

The major atmospheric circulation pattern that sets the climate of the southwestern US apart from the rest of the US is the North American Monsoon (NAM). NAM is experienced as a pronounced increase in rainfall between mid-June to September delivering up to 65% of annual
precipitation (Adams and Comrie 1997). Daily, local-scale variability in monsoon precipitation is linked to the geographic distribution and nature of air mass thunderstorms, as the monsoon is fueled by dual sources of moisture from the Pacific Ocean and the Gulf of California. Adams and Comrie (1997) highlight low-level moisture surges, which transport atmospheric moisture northward from the Gulf of California as one mechanism responsible for *intraseasonal* monsoon precipitation variability. The timing of the majority of precipitation during the monsoon, which coincides with high rates of summertime potential evapotranspiration (PET) due to high air temperatures, exacerbates water scarcity in the basin. Estimated at ten times the amount of annual rainfall in the lower elevations, the high summertime PET reduces the amount of water available to naturally recharge the aquifer (Pool and Dickinson 2006). Recharge in the basin is also sensitive to El Niño Southern Oscillation (ENSO), which can cause high interannual variability in winter precipitation. Principal recharge of the alluvial aquifer, which holds much of the available groundwater in the upper basin, depends on streambed infiltration and mountain front recharge (Pool and Dickinson 2006).

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

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

A primarily natural driver of change in semi-arid riparian systems is a decrease in the winter rain dominance of annual precipitation, which impacts the fundamental processes of resource distribution and winter flooding through which a keystone riparian tree species, the Freemont cottonwood, propagates. Generation of new patches of Freemont cottonwood and Gooding’s willow requires periodic flood disturbance by channel migration and channel widening, as these processes create seedbeds for recruitment of young trees (Dixon et al. 2009). A trend of decreasing winter precipitation and an almost 30-year gap between winter flood pulses has altered vegetation dynamics by impeding seed transportation and reducing small-scale disturbances important for maximizing diversity by removing biomass and redistributing resources (White and Stromberg 2011). Furthermore, research employing a range of potential future climate models found that under every scenario, cottonwood-willow forest patch area in the Upper San Pedro river riparian corridor declined because projected rates of future channel migration and seedling recruitment were insufficient to counterbalance the loss of established riparian forests by senescence and erosion (Dixon et al. 2009).

Methods and Data Analysis

To fulfill the objectives and answer the research questions identified earlier, this research utilized an interdisciplinary, mixed methods approach (Table 1). The methodology for data collection and analysis relied on interviews with key informants, archival research and historical document review, spatial analysis and synthesis of binational datasets, and land use classification and change detection at the watershed scale using methods from remote sensing and geographic information systems (GIS).
Semi-structured Interviews, Participant Observation, and Public Meeting Attendance

I conducted 29 semi-structured interviews with key informants including natural resource managers, ranchers, local residents, and political figures key in communities in southern Arizona and northern Sonora, and in the capital city of Hermosillo, Sonora between 2012 and 2015 (Table 2). Interviews were carried out in English and Spanish. The large majority of respondents were male due to the demographics of ranching and agriculture in the *ejido* communities, which tend toward male-dominated labor, and the tendency for natural resource managers, in both the Arizona and Sonora portions of the watershed, to be male. Interview questions focused on livelihood and natural resource management activities, with emphasis on activities located in or dependent on the riparian zone, water and land use, impacts of drought, changes in water and land use practices and/or management strategies over time and the drivers of these changes, and more general changes noted over time to the riparian habitat.

In addition to the interviews, my visits to the *ejido* communities also included participant observation of farming and ranching activities. Participant observation occurred in the Spring of 2014 in two *ejido* communities in the Mexican-portion of the San Pedro River: Ejido Jose María Morelos and Ejido Emiliano Zapata. These visits tended to focus on livelihood activities carried out in or near the riparian zone. In relation to agriculture the focus was on irrigated floodplain cultivation utilizing a mix of groundwater and surface water resources. In relation to ranching, the focus was on grazing of livestock in the riparian zone and, beyond the riparian zone in the expansive high-elevation grasslands. In the US-portion of the San Pedro River riparian corridor, I conducted 3 walk-alongs with Bureau of Land Management (BLM) officials, the agency responsible for the riparian conservation area. During these walk-alongs, I observed how managers conducted their daily activities, their interactions with different species, including
endangered plants and animals, rare birds, and invasive species, and the discourses used to refer to the river, the riparian habitat, and to different water user groups. The participant observation of agricultural activities in Sonora and the walk-alongs in Arizona imparted knowledge about historical changes in conditions of the riparian zone, historical legacies and contemporary shifts in how land, water, and other riparian zone resources are used and understood, and opinions about who is most exposed to suffer from and additionally who is to blame for water scarcity and water pollution problems.

To understand the management of the riparian zone of the section of the upper San Pedro River on the US-side of the border, most of which is enclosed in a national conservation area, I attended 23 public meetings and 3 wet/dry mapping events during the period 2011-2015 (Table 3). The majority of the public meetings were meetings of the Upper San Pedro Partnership (USPP) Policy Advisory Committee (PAC), an advisory body composed of representatives of 23 governmental and non-governmental organizations united by a common concern for preserving the health of the riparian zone of the San Pedro River. Four of the meetings I attended were held by the Bureau of Land Management (BLM) as part of their planning process and public education initiative for the forthcoming Resource Management Plan for the San Pedro Riparian National Conservation Area (SPRNCA). These meetings included scoping forums, educational events, and public comment periods. During the second Saturday of June in 2012, 2013, and 2015, I attended Wet/Dry Mapping events coordinated by The Nature Conservancy (TNC), which have participants walk specific lengths of the river measuring areas of flowing water and areas of dry riverbed.

To analyze the data collected from the interviews, participant observation, and meeting attendance, I used a mixture of inductive and deductive approaches to code responses and field
notes both by categories hypothesized to be important \textit{a priori}, such as water and land use practices, and riparian resource management strategies, and allowing the emergence of new categories from the data, such as types of discourses around water user groups and types of natural resource governance.

\textit{Archival Research}

I conducted archival research in Arizona in Tucson and Sierra Vista and in Mexico in the cities of Hermosillo, Cananea, and Mexico City (Table 4). Archival research focused on the identification, close reading, and textual analysis of primary and secondary sources, including: government publications, legal and policy documents, newspapers, and natural resource management agency reports. Each archive provided different collections of source material that proved useful for piecing together the social and environmental history of the binational San Pedro riparian corridor. The Arizona Historical Society’s collection in Tucson, Arizona contains historical records and maps from the nineteenth and twentieth centuries describing the changing ownership of the San Pedro River riparian corridor land on the Arizona side of the international border. In this archive, I also found transcripts of public meetings and the record of public comments submitted in response to resource conservation plans and the implementation of the SPRNCA in 1988. The Cochise County Historical Society provided access to the Sierra Vista Herald newspaper archive. These data were particularly useful for tracing the history of property claims, land use, and the birth of riparian conservation discourse and its discontents within the U.S. San Pedro; information on which I relied heavily to support the comparative historical analysis of conservation outlined in \textit{Appendix C: Uneven Conservation of Binational Riparian Resources: Institutional Conflict, Ecological Uncertainty, and Community Organization}. 
In Hermosillo, Mexico, the collection at the Archivo General del Estado de Sonora contains a rich documentation of primary texts from the late nineteenth and early twentieth centuries, including the founding of the original copper mine in Cananea and the cattle empire built by Colonel William Greene, official military telegrams and personal letters from Cananea during the Mexican Revolution, and records of land ownership in the Mexican San Pedro. The collection at the Biblioteca Fernando Pesqueira proved invaluable, in particular, the complete historical set of the Diario Oficial de la Federación (DOF), containing all formal government publications, including ejido establishment records, expropriation rulings, and the announcement of new laws and changes to the existing legal code. The Biblioteca also provided access to newspaper archives for the El Impacial and the El Sonorense for the decades 1950-1970, a key period of social upheaval and ecological change in the San Pedro watershed. The state and national archives of the Registro Agrario Nacional (RAN) located in Hermosillo and Mexico City contain court rulings for agrarian disputes, including contested land sales in ejidos, overflowing folders detailing PROCEDE cases for the delineation and privatization of ejido lands following the landmark 1992 constitutional changes to Mexico’s Article 27, and detailed rosters of changing ejido membership and governance. I rely on these data from the archives in Mexico to reconstruct the early history of extractive industry in the region and to provide local historical and geographical context leading up to the contested formation of the seven collective ranching ejidos in Mexican San Pedro in the late 1950s. These data are also used as evidence to support the argument for the three mechanisms of riparian enclosure (privatization, expropriation, and conservation) that I introduce in Appendix B: Social-Ecological Transformations in Riparian Zones: The Production of Spaces of Exclusion and the Uneven Development of Resilience in the Sonoran Borderlands.
Spatial Data Analysis and Synthesis

Groundwater well concession data were collected from Mexico’s National Water Commission (Comisión Nacional de Agua, CONAGUA) and analyzed using geographic information systems (GIS) software to geocode and conduct spatially analysis of the point locations of the wells with respect to type of user, volume of concession, and maximum allowable depth of the well. A limitation of this data source is that the concession data is only a proxy measure for the well. Data about actual well pumping volumes and depths are not collected in the watershed. Using the concession data as a proxy introduces two possible types of error. First it is possible to over-estimate the number of actual drilled wells, the pumping volumes of the actual wells, and the depths that the wells have been drilled. Conversely, it is also possible to under-estimate these same metrics, as more wells may have been drilled than stated in the concessions, the wells may be pumping higher volumes of water, and may be drilled to deeper depths, due to the lack of regulation and oversight in the region (Scott 2013).

I collected data on agricultural production and grazing subsidies from representatives of Mexico’s Secretary of Agriculture, Ranching, Rural Development, Fishing, and Food (SAGARPA, Spanish initials). Data was analyzed to determine trends over time and to corroborate data from interviews with local producers. Finally, I analyzed text and collected data from published reports from Grupo México, the transnational corporation that owns and operates the Buenavista del Cobre mine located in Cananea, Mexico at the headwaters of the San Pedro River. I also synthesized watershed and aquifer studies published by scientists and water management agencies in the US and Mexico to quantify change in the aquifer water balance, in particular changes over time in extraction of groundwater to better understand the rate of aquifer
Remote Sensing and Change Detection

To analyze how land cover has changed in the San Pedro River watershed over time, my co-author (David Chan) and I performed a 10-class land cover classification of the binational San Pedro watershed for the year 2010. Utilizing multi-temporal imagery from NASA’s Landsat 5 Thematic Mapper (TM), we followed a sophisticated Classification and Regression Tree (CART) approach to derive an updated, high accuracy (kappa=0.7511), 10-class land cover classification that matches the land cover categories used in the previous series of land cover maps. The CART method utilizes a combination of algorithms coded within See5, a data mining software, and ERDAS Imagine to construct the statistics-based decision tree used to classify the image data. The final 2010 land cover map product has an overall accuracy of 77.6%, which a review of the remote sensing literature found to be acceptably high, as 85% represents the highest accuracy possible with current methods. Land cover change over time was assessed through two methods: 1) relative proportional change of each land cover class; and 2) post-classification change detection. The first method is used to assess broach trends in land use and land cover change over several decades, but has the disadvantage of not being spatially explicit. The second method demonstrates a spatially explicit assessment of land cover change.

Key Findings and Contributions of the Dissertation

This dissertation contributes four findings to advance understanding of the drivers and consequences of riparian SES transformations and of shifting natural resource governance in a semi-arid transboundary watershed faced with managing multiple, competing demands for water that outpace supply. The findings of this dissertation are generalizable beyond the bounds of the
San Pedro River study area. Few previous studies have applied models of SES transformation – Gunderson and Holling’s adaptive cycle model and Ostrom’s SES framework – to analyze endogenous and exogenous drivers and consequences of social and ecological change in binational dryland riparian corridors. For researchers, this study provides a method for conducting integrated research in a binational context and for synthesizing multiple social and environmental datasets to trace spatially explicit change over time in a riparian SES. For policy makers, the findings provide empirical evidence to: 1) demonstrate the importance of collecting, integrating, and synthesizing data across international boundaries to build robust datasets that holistically examine binational SES, based on physical, rather than political bounding objects (i.e. physical watershed boundaries rather than political nation state boundaries); 2) inform decision-making about the obstacles that can hinder the political process of establishing riparian conservation; and 3) reveal how shifts in property rights regimes and political economic systems produce feedback loops and disturbances capable of triggering transformational events in coupled natural systems.

First, drawing concepts from political ecology and social-ecological systems theory into conversation with scholarship on water security, I introduce a definition of water security that focuses attention on issues of access, livelihoods, sustainable production, and resilience. Following this definition, I propose a conceptual framework for assessing water security based on three interrelated indicators: 1) the exposure to harm or hazard, which I refer to as risk; 2) the capacity to respond to and cope with disturbance while maintaining system structure and function — the definition of resilience; and 3) the expectation and enforcement of who will be held accountable following exposure, which I refer to as responsibility. By locating water security at the intersection of these three indicators, I argue that it becomes possible to assess
different conditions of water security and exposure to insecurity both between and within economic sectors and livelihoods within a region. Detailing two interrelated empirical cases, I highlight the uneven topographies of water security in the San Pedro River. The first case focuses on the impacts of increasing groundwater extraction and territorial expansion by the local copper mining industry on the livelihoods of small-scale agricultural producers downstream of the mine. The second case focuses on the reconfiguration of collective ranching livelihoods as a result of both the mine’s water consumption and concomitant territorial expansion and ongoing neoliberal shifts in natural resource management institutions. For each case, I utilize my proposed conceptual framework for water security to assess water security at a community scale, demonstrating that for similar livelihood strategies, water security conditions differ based on social, spatial, and biophysical factors.

Second, by synthesizing binational sources of water consumption data, my dissertation research reveals that groundwater pumping in the Mexican-portion of the binational San Pedro River aquifer is far greater than previously reported. I conducted a spatial analysis of groundwater concession data collected from Mexico’s national water agency, Comisión Nacional de Agua (CONAGUA). The data contains records for the years 1997 to 2014 that include the owner of the concession and the location, maximum depth, and maximum volume approved for the well. My analysis of the groundwater concession records finds that current annual volume of approved groundwater concessions (approximately 89 cubic hectometers) far exceeds the published sustainable rate of natural recharge for the aquifer of 24 cubic hectometers per year (DOF 2009). Thus, the aquifer is in an unsustainable state of over allocation. According to Mexico’s 2004 reform of the Law of National Waters (LAN), in aquifers where groundwater extraction exceeds the rate of natural recharge new concessions are mandated to cease
Instead, existing concessions can be traded through a groundwater market. The findings of this analysis are significant as they reveal: 1) CONAGUA continues to grant new groundwater concessions in spite of extraction rates from the aquifer far above the published rate of natural recharge; 2) the Buenavista del Cobre copper mine, owned and operated by the transnational corporation Grupo México controls the vast majority of the groundwater concessions (72.5%); and 3) across the Mexican portion of the San Pedro River watershed the largest volume and deepest well concessions are statistically significantly spatially clustered at the river’s headwaters, near Cananea, in the mine’s well fields.

This finding dispels existing widespread myths that farmers and ranchers are responsible for high water consumption in the Mexican portion of the basin. Previous research treated the binational watershed and the associated underground aquifer as two distinct basins and thus did not assess the combined total water consumption in the Arizona and Mexican portions of the basin, leading these reports to overlook the over-allocation of water supplies. For this reason, I argue that an integrated, spatially explicit geographic analysis that synthesizes data across the entire watershed is necessary for understanding how and why transformations are occurring in riparian zones and possible future solutions. For example, an additional spatially explicit analysis of the distribution and depths of wells in the watershed demonstrates that many of the deepest and highest consumption wells in Mexico are located in the floodplain zone within the riparian corridor at the headwaters of the river. Previous hydrologic research determined that pumping in the riparian zone leads to disproportionately high reductions of surface water availability in the river channel (Stromberg et al. 1996; ADWR 2002; Lite and Stromberg 2005). The findings from this article offer important insight for researchers, policy-makers, and stakeholders who require integrated, up-to-date information for decision-making.
Third, my research findings offer an empirical contribution to political economy scholarship through the identification of three legal mechanisms that are facilitating the dispossession of small-scale agriculturalists and the enclosure of high-value riparian spaces. Enclosure is the process of divorcing a producer from his/her means of production. In riparian zones, this tends to be experienced as a loss of ability to access surface and groundwater resources, fodder and forage materials for cattle, and nutrient rich, irrigable cropland. The three mechanisms I identify are: 1) privatization – the exclusive, alienable rights to land and water resources; 2) expropriation – the seizure of land and transfer of property rights to another individual, as well as capture of water and physical transfer out of the riparian zone and legal-institutional transfer of concession rights to another water user; and 3) conservation – based on models that prohibit all agricultural and ranching activities within the conservation area. Taken together, these three legal mechanisms have contributed to a significant shift in the balance of power in the bi-national watershed. Small-scale agriculturalists are losing power as land and water resources are consolidated under the control of the Buenavista del Cobre copper mine, the third largest copper producer in the world, located in Cananea, Sonora, at the rivers’ headwaters. The identification of these three mechanisms of enclosure helps to elucidate the interrelations among law, global political economy, and social-ecological transformation in borderland riparian spaces.

Fourth, this dissertation presents an updated 2010 land use and land cover classification map for the binational watershed, extending the temporal coverage of the San Pedro River watershed land cover dataset to 37-years (1973-2010). This updated land cover data provides an opportunity to analyze recent land use and land cover changes in the watershed at an enhanced level of detail (30 meter spatial resolution) over the older series of maps, which used coarser-
scale imagery (70 meter resolution). The accompanying change detection analysis offers a spatially explicit assessment of changes at both the binational watershed scale and zooms in to assess changes in the riparian corridor. Thus, the analysis is useful for assessing spatially explicit change at multiple scales. The 2010 land cover map we present responds to a need of local decision-makers and natural resource management agencies for updated data to run hydrological and ecological simulation models, to conduct vulnerability assessments related to future climate change impacts, and for scenario-planning activities. The last available land cover map is based on 1997 imagery and was derived from a lower accuracy image interpretation method. Thus, future planning for riparian conservation, land use, and water management in the San Pedro River watershed has been utilizing land cover conditions nearly 20 years out of date. The 2010 dataset also provides the opportunity to conduct a much-needed assessment of the changes in the spatiality of riparian cover within the boundaries of riparian conservation area between its pre-establishment conditions in 1986 (the SPRNCA was established in 1988) and 2010.
REFERENCES


Davidson, D.J. 2010. The applicability of the concept of resilience to social systems: Some sources of optimism and nagging doubts. Society and Natural Resources 23: 1135-1149.


**TABLE 1: Research objectives and methods**

<table>
<thead>
<tr>
<th>Objective 1: To examine how shifts in social and ecological systems have transformed riparian spaces in the transboundary San Pedro River watershed</th>
<th><strong>Data Collection and Analysis Methods</strong></th>
</tr>
</thead>
</table>
| How are social-ecological processes at the watershed scale affecting access to water resources in the riparian zone? | • Semi-structured interviews  
• Participant observation  
• Meeting attendance  
• Land use/land cover classification  
• Spatial analysis of groundwater concession data  
• Archival research |

<table>
<thead>
<tr>
<th>Objective 2: To assess the consequences of riparian transformations for the human and biophysical communities who depend on riparian resources for survival</th>
<th><strong>Data Collection and Analysis Methods</strong></th>
</tr>
</thead>
</table>
| How are shifting relations of access to water and riparian zone resources influencing and differentiating levels of exposure to hazards over space and across time? | • Semi-structured interviews  
• Participant observation  
• Land use/land cover classification  
• Document analysis  
• Archival research |

| Following a disturbance event, how are capacity to respond and recover from disturbance and expectations of accountability shifting over space and across time? | • Semi-structured interviews  
• Participant observation  
• Land use/land cover classification  
• Document analysis  
• Archival research |
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<th>Year</th>
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<td>Douglas, AZ</td>
<td>2012</td>
</tr>
<tr>
<td>2</td>
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<td>Mayor, City of Sierra Vista</td>
<td>Sierra Vista, AZ</td>
<td>2012</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>Region Director, Bureau of Reclamation</td>
<td>Tucson, AZ</td>
<td>2012</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>Field Technician, Bureau of Land Management, Cochise County</td>
<td>Sierra Vista, AZ</td>
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</tr>
<tr>
<td>6</td>
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<td>Sierra Vista, AZ</td>
<td>2012</td>
</tr>
<tr>
<td>7</td>
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<td>2012</td>
</tr>
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<td>M</td>
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<td>Hermosillo, MX</td>
<td>2012</td>
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<tr>
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<td>M</td>
<td>Rancher, U.S. San Pedro</td>
<td>Sierra Vista, AZ</td>
<td>2013</td>
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<td>F</td>
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<td>Cananea, MX</td>
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<tr>
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<td>2014</td>
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<td>2014</td>
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<td>2014</td>
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<td>26</td>
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<td>2014</td>
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<tr>
<td>29</td>
<td>M</td>
<td>Acting Director, Bureau of Land Management, Cochise County</td>
<td>Tucson, AZ</td>
<td>2015</td>
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**TABLE 3**: List of observed meetings, 2011-2015

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<td>6</td>
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<td>5/9/2012</td>
</tr>
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<td>7</td>
<td>Wet/Dry Mapping of the San Pedro River riparian zone</td>
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<td>6/9/2012</td>
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*Note, due to budget cuts, the USPP meetings were cut from monthly to 4 times a year to 3 times a year between 2012 and 2015*
**TABLE 4:** List of archives visited, 2012-2015

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<td>2</td>
<td>Cochise County Historical Society</td>
<td>Sierra Vista, Arizona</td>
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<td>3</td>
<td>Cananea City Museum and Archive</td>
<td>Cananea, Mexico</td>
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<tr>
<td>4</td>
<td>Registro Agrario Nacional (RAN) State Archive</td>
<td>Hermosillo, Mexico</td>
</tr>
<tr>
<td>5</td>
<td>Archivo General del Estado de Sonora (Archive of the State of Sonora)</td>
<td>Hermosillo, Mexico</td>
</tr>
<tr>
<td>6</td>
<td>Biblioteca Fernando Pesqueira (State of Sonora Newspaper Archive)</td>
<td>Hermosillo, Mexico</td>
</tr>
<tr>
<td>7</td>
<td>Registro Agrario Nacional (RAN), Federal Archive</td>
<td>Mexico City, Mexico</td>
</tr>
<tr>
<td>8</td>
<td>Archivo General de la Nación (National Archive)</td>
<td>Mexico City, Mexico</td>
</tr>
</tbody>
</table>
FIGURE 1: Map of the binational San Pedro River watershed spanning the border between Sonora, Mexico and Arizona, U.S. (Image by author).
FIGURE 2: Map of the location of the collective ranching *ejido* communities in the Mexican-portion of the watershed (Image by author).
FIGURE 3: Photo of the *Buenavista del Cobre* mine located in Cananea, Mexico in the headwaters of the San Pedro River (Photo by author).
FIGURE 4: Photo of the riparian zone of the San Pedro River during the high flow period of the summer monsoon (Photo by author).
FIGURE 5: Photo of a mine-controlled groundwater well in the riparian zone of Ejido Vicente Guerrero (Photo by author).
**FIGURE 6:** The panarchy model (source: Holling and Gunderson 2001), representing the four phases of the adaptive cycle: exploitation (r-phase), conservation (K-phase), release (alpha-phase), and reorganization (omega-phase). The r-phase and K-phase (front loop) take inspiration from ecological models that designate the exploitative phase as dominated by r-strategists and the conservation phase as dominated by K-strategists. The arrows represent the speed of the transition: short, closely spaced arrows indicate the slow front loop, while long arrows indicate the rapid transition through the back loop. The x-axis represents the degree of connectedness, which is high in the conservation and release stages. The y-axis represents potential inherent in the accumulated resources, which is high in the reorganization and conservation stages.
APPENDIX A


Lily A. House-Peters

Christopher A. Scott

For submission to Water Alternatives

Abstract

In northern Sonora, Mexico, rapid growth and expansion of industrial copper mining in the San Pedro River watershed is depleting the regional aquifer, producing conditions of water insecurity and social-ecological precarity for livelihoods based on agriculture and ranching based livelihoods. To analyze and assess water security across livelihood pathways within the watershed, I introduce a conceptual framework that draws on three interrelated processes: exposure to harm or hazard (risk); ability to cope with exposure and maintain functionality (resilience); and problem framing and associated expectations of accountability for exposure to harm or hazard caused (responsibility). This research draws on data from interviews, spatial analysis of groundwater concession data, and analysis of agricultural production and subsidy data. I detail two empirical cases highlighting the uneven topographies of water security within and between livelihood sectors. The first case focuses on the impacts of increasing groundwater appropriation and territorial expansion by the mining industry on the livelihoods of small-scale agricultural producers downstream of the mine. The second case focuses on the reconfiguration of collective ranching livelihoods as a result of both the mine’s water consumption and concomitant territorial expansion. Both cases require attention to ongoing neoliberal shifts in natural resource management institutions. For each case, I use the proposed conceptual framework to assess changes in water security at household and community scales in a watershed context, demonstrating that for the same livelihood pathway, water security conditions differ based on social (class, gender) and spatial (riparian access), and biophysical (hydrologic seasonality, land quality) factors. The analysis also draws explicit attention to the mine’s accountability for the production of water insecurity in the watershed, calling for a rethinking of both problem framing and resilience-enhancing strategies leading to more equitable outcomes.
Introduction

Across Latin America, transnational mega mining operations have become some of the largest and most influential landowners and change agents at the watershed scale (Bury 2004, 2005; Bebbington et al. 2008; Perreault 2013; Andreucci and Radhuber 2015; Avci 2015). Large-scale mineral extraction and concentration processes demand high volumes of water and produce large amounts of toxic wastewater, laden with heavy metals, acids, and other industrial waste byproducts with long afterlives (Perreault 2014). Bury et al. (2013) refer to the mining sector in Peru as a ‘force of change’ as its activities result in changes downstream in the timing, magnitude, and quality of surface water flows and in the dynamics of aquifer recharge and groundwater depletion and pollution. The seemingly unbridled growth of extractive industry throughout the watersheds of Latin America, and the global South more broadly, is transforming hydrological processes and reconfiguring social and ecological relations. The privileged position mining tends to be afforded in neoliberal-leaning, and even counter-neoliberal (Andreucci and Radhuber 2015), governments means that often-competing water users are left to experience water shortage and polluted water supplies (Perreault 2014).

Water security presents a malleable analytical framework that I argue can attend to the political-economic concerns of access, livelihoods, and production, while also incorporating the socio-ecological system (SES) variable, resilience. The integration of political and socio-ecological variables within water security enables research to examine drivers and outcomes of SES transformation. Additionally, empirical scholarship on water security increasingly is focused on developing and using indicators to assess water security conditions, an approach that depends on the development of metrics. Definitions of water security are diverse, attending to a wide range of variables. How water security is defined is important, because the definition can
drive the development of indicators, thus focusing attention to certain considerations, while eliding others. For example, Grey and Sadoff (2007) are the first to explicitly include livelihoods in their definition of water security, which states “the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environment and economies” (p. 547-548). The focus on livelihoods is critical for the study of water security in rural regions where the rapid growth of extractive industry competes with agrarian communities for control over limited water supplies. Attentive to the concepts of livelihoods, access, production, and resilience, I define water security as: *access to adequate quantities of water of acceptable quality to support livelihoods and sustainable production to ensure resilient human and ecological communities*. The definition I propose is influenced by previous definitions of water security across the literature, drawing on the work of Grey and Sadoff 2007, Bakker 2012, Norman et al. 2013, and Scott et al. 2003.

Distributional inequalities lead to serious water security concerns for rural livelihoods and peasant viability (Bebbington 1999, 2000; Budds and Hinojosa 2012; Perreault et al. 2012). In many locations, rural subsistence communities are experiencing a three-pronged attack to their livelihood viability. The mining sector not only reduces access to water and land through its direct consumption of these resources, but its activities also serve to transform environmental processes beyond the boundaries of the mine, further impacting resource cycles on which agrarian livelihoods depend (Bebbington et al. 2008). Concomitant with these processes of consumption and transformation is the ongoing withdrawal of social protections as states retract, privatize, and decentralize regulatory functions. Thus, rural communities find themselves
‘dangerously exposed’, a term Evans and Reid (2013) evoke to describe situations where vulnerability becomes the very precondition on which life is based.\(^3\)

In the headwaters of the transnational San Pedro River (Figure 1), in semi-arid northern Sonora, Mexico, water security concerns are paramount and increasing. Rapid growth and expansion of industrial copper mining is severely impacting water quantity and quality, producing conditions of water insecurity and economic and ecological precarity for agriculture- and ranching-based livelihoods. The co-existence of enormous mineral wealth and a long history of agricultural production and cattle ranching in a water-limited environment has resulted in multiple, competing demands for water that outpace available supply. Throughout the 20\(^{th}\) century modern agrarian politics in Mexico have been shaped by the processes of concentration and dispossession necessary for capitalist growth. Although land reform was the backbone of Mexican revolutionary ideology, in the latter half of the twentieth century, consensus moved away from the political sector and began to coalesce around economic progress, led by a nationalist producer class (Sanderson 1981). Accompanying this transition, there was a retraction of the trademark rural development and land redistribution programs that emerged after the Mexican Revolution and previous support of the agricultural sector shifted to policies in support of the proletarianization of landless peasants to instead join the industrial labor force.

The article proceeds as follows. In the next section, I review the literature to present the theoretical background for this case study, drawing the water security literature into direct conversation with key concepts from human-environment geography and social-ecological

\(^3\) The retraction of the social protections for the peasantry from the State does not ignore the long history of State violence suffered by peasants in Mexico and across Latin America and the vulnerability and dangerous exposure experienced prior to the neoliberal turn. One example from 1975 in Sonora portrays a common experience of State violence for \textit{ejidatarios}: “At dawn on October 23, 1975, more than 20 residents of San Ignacio Río Muerto in the northern Yaqui valley fell wounded at the hands of the Sonoran state authorities; 7 died” (Sanderson 1981: 3).
systems (SES) theory. Next, I propose a conceptual framework for analyzing and assessing water security that draws on three interrelated processes: exposure to harm or hazard (risk); ability to cope with exposure and maintain functionality (resilience); and problem framing and associated expectations of accountability for exposure to harm or hazard caused (responsibility). In the fourth section, I outline the methodology for data collection and analysis and introduce the study area. The fifth section details two interrelated empirical cases highlighting the uneven topographies of water security in the San Pedro River watershed in the northern Sonora, Mexico, bordering the United States. The first case focuses on the impacts of increasing groundwater extraction and territorial expansion by the local copper mining industry on the livelihoods of small-scale agricultural producers downstream of the mine. The second case focuses on the reconfiguration of collective ranching livelihoods as a result of both the mine’s water consumption and concomitant territorial expansion and ongoing neoliberal shifts in natural resource management institutions. For each case, I use the conceptual framework for water security introduced in Section 2 to assess water security at a community scale, demonstrating that within the same economic livelihood sector, water security conditions differ based on socio-spatial and biophysical factors. The final section discusses the results for each empirical case and concludes the article.

**Theoretical Background**

Attention to social-ecological transformations wrought by the extraction of mineral resources is a growing emphasis of academic scholarship, especially in the fields of environmental justice and political ecology. Recently, access has come into clear focus in the water security literature, with definitions increasingly engaging the term. For example, there is
an important shift in language evident between Bakker’s well-cited definition from 2012, “an acceptable level of water-related risks to humans and ecosystems, coupled with the availability of water of sufficient quantity and quality to support livelihoods, national security, human health, and ecosystem services” (Bakker 2012: 914) and a flurry of subsequent definitions published in 2013 and 2014 that place the concept of access front and center in water security studies. Norman et al. (2013) begin the trend, defining water security as “sustainable access, on a watershed basis, to adequate quantities of water, of acceptable quality, to ensure human and ecosystem health” (538). McEvoy (2014) and Jepson (2014) invert this formulation, focusing on the role that lack of access plays for the production of water insecurity. McEvoy (2014) presents a definition of water insecurity as “the lack of access to, or unavailability of, sufficient, clean, affordable, and reliable potable water and sanitation” (521), which parallels Jepson’s (2014) argument that “gaps in water reliability, quality, and access erode the functioning necessary for basic human existence” (109). Yet very few water security studies have engaged directly with the impacts of extractive industry on access to sufficient and clean water supplies.

In calling for a “political ecology of the subsoil,” Bebbington (2012) implores researchers to attend to the intersections between the extractive economy, livelihoods, and contemporary governance structures, through a lens trained on the co-constitution of mineral resource extraction and wider capitalist political, economic, and institutional arrangements. In critical water resource geography, scholars have animated the concept of the ‘waterscape’ to interrogate linked processes of environmental transformation, marginalization, and social exclusion in relation to the expanding mining sector in Peru (Budds and Hinojosa 2012; Perrault et al. 2012). The waterscape concept has gained purchase with critical scholars due to its explicit focus on “the ways in which flows of water, power, and capital converge to produce uneven socio-
ecological arrangements over space and time” reflecting dominant power relations (Budds and Hinojosa 2012: 124). Although as an approach the ‘waterscape’ is compelling, it lacks the capability of assessment, a feature more robustly developed in the burgeoning water security scholarship.

In the context of analyzing extractive industry in Latin America, the role of neoliberal state restructuring on the politics of water allocation, distribution, and the regulation of polluted wastewater disposal has been an active area of research. This line of research draws on an earlier tradition of analyses of the implications of neoliberal reforms in water governance, such as the privatization, commodification, marketization, and commercialization of water resources, on social relations, livelihoods, and the environment (Bauer 1998, 2004; Bakker 2005; Perreault 2005, 2008). Through neoliberal reform social-ecological relations are transformed, as all domains of life (economic, political, cultural, environmental) become increasingly refracted through an economic lens focused on producing exchange value. Questions that follow from this approach include “Who makes resource decisions, for the benefit of whom, at whose expense, at what sociospatial scales, and through what institutional arrangements?” (Perreault 2008: 834).

The concept of ‘accumulation by dispossession’ (Harvey 2003) has also been applied to examine the ongoing processes of water privatization and neoliberal reform and their intersection with the growth of extractive industry (Ahlers 2010; Perreault 2013). Ahlers (2010) utilizes ‘accumulation by dispossession’ to identify how water allocation and distribution has been reconfigured through devolving management and shifting property regimes to facilitate the consolidation of control over water rights by the private sector. In a semantic inversion of Harvey’s formulation, Perreault (2013) introduces the term ‘dispossession by accumulation’ to conceptualize the accumulation of toxic waste and other negative externalities that serve to
remove water and land from production. Thus, as profit accumulates in one sector, insecurity and
risk may accumulate in other sectors and spaces as resources become unavailable. These
analytical frameworks are particularly useful for analyzing social, economic, and political
dynamics, but one drawback is that they often do not explicitly account for coupled SES
dynamics.

Drawing SES theory into conversation with water security, Scott et al. (2013) propose a
definition of water security that introduces the resilience dimension, “The sustainable availability
of adequate quantities and qualities of water for resilient societies and ecosystems in the face of
uncertain global change” (281). The authors argue that the inclusion of resilience serves to
reformulate water security away from static conceptualizations that “inadequately address
mutually interactive coupled human-natural dynamics” (Scott et al. 2013: 281). Rather, by
including resilience, water security is enabled to identify possibilities for recovery in systems
experiencing water insecurity and adaptation is heralded as a necessary component of pursuing
water security. Resilience, one of three fundamental properties that comprise the adaptive cycle
model of SES theory, is defined as the magnitude of shock, or amount of disturbance, that a
system can absorb while maintaining its current structure and composition, hence not
transitioning to an alternative system state (Holling and Gunderson 2002). As a key feature of
SES theory, resilience is founded on an understanding that the human domain and the
biophysical domain are interdependent and co-constitutive, as transitions in one part of the
system feedback to affect other system components (Walker and Salt 2006).

Scholarship in human-environment geography demonstrates the importance of
understanding how relations between natural resources and power intersect to shape differential
outcomes among diverse social groups, producing uneven topographies of access to natural
resources within and between communities (Swyngedouw 1999; Birkenholtz 2009, 2013; Bakker 2010; Sultana 2010, 2012, 2013; Budds and Sultana 2013). Rather than being natural occurrences, conditions of insecurity are recognized as products of social relations and processes. Resource struggles cannot be extricated from the politics of struggle over particular spaces and management approaches. Transformations of SES relations are experienced differently (Stanley 2013) as subjects experience uneven exposure to vulnerability due to historic and existing differences in access to resources, capital, and aid during periods of scarcity and crisis. Or said another way, processes and events that reconfigure social-ecological power relations often result in the exacerbation, rather than the amelioration, of difference and marginalization.

Thus, human and biophysical communities and individuals within communities are unevenly positioned in relation to risk, resilience, and responsibility. On the ground, this means that communities experience different levels of exposure to harm and hazard, distinct abilities to cope with disturbance events, and are positioned asymmetrically at the receiving end of enforced structures of accountability. I argue that this unevenness is exacerbated by contemporary transformations of historical regimes of access to natural resources, such as land and water, and increasing levels of environmental degradation and pollution. The result is a spatially and temporally uneven topography of water (in)security following social-ecological system shocks and disturbances, such as drought, aquifer depletion, and toxic spills.

Conceptual Framework

I propose a conceptual framework to guide the analysis and assessment of water security (Figure 1). This framework is based on three interrelated indicators: 1) the exposure to harm or hazard, which I refer to as risk; 2) the capacity to respond to and cope with disturbance while
maintaining system structure and function — the definition of resilience; and 3) the expectation and enforcement of who will be held accountable following exposure, which I refer to as responsibility. By locating water security at the intersection of these three indicators, it becomes possible to assess the differentiation of experiences of water security and insecurity both between and within economic sectors and livelihoods in a region. Although some definitions of water security focus on watershed-level security, I argue that the watershed focus can serve to obscure wide variance of experience of security and insecurity across communities within the watershed. For example, while some communities and livelihood sectors may experience acute water insecurity, others nearby may be insulated from the negative effects. At a community or economic sector scale, I suggest that assessing the triad of proposed indicators (exposure to harm or hazard; ability to cope with disturbance once exposed; and norms and enforcement of accountability) can reveal important sub-watershed scale differences in water security and offer creative solutions to assist recovery from water insecurity.

Through the framework, I synthesize insights from diverse fields including political ecology, critical risk studies, and SES theory. In the figure, the water security is located in the middle of the diagram, nested within three indicators of water security: risk, resilience, and responsibility. These indicators are further nested within a sphere of eight ecological indicators of dryland riparian system functioning: streamflow permanence; ecological diversity; riparian habitat; water quality; aquifer storage; spring discharge; near stream alluvial aquifer water levels; and baseflow discharge. These eight indicators are derived from indicators developed by the US Geological Survey’s (USGS) to assess the condition of the San Pedro River riparian corridor. The model recognizes bidirectional feedbacks between the coupled social and ecological indicators represented by the permeable, dashed line of the inner sphere and the arrow. Locating
water security at the center of these social and ecological dynamics provides an assessment framework that recognizes both political-economic and social-ecological drivers of differentiated experiences of water security and insecurity. This framework has been developed specifically for a dryland riparian SES and for the context of investigating the water security of rural livelihoods threatened by the expansion of extractive industry, but it could be modified to fit other contexts.

The marrying of resilience and a political ecology approach introduces potential challenges and critiques, but also presents positive opportunities. Resilience has come under heavy critique from critical scholars in geography and political ecology, in particular for what some identify as a central paradox at the heart of resilience: that the long-term success of capitalism is predicated on uneven development, which serves to erode and undermine resilience itself (Mackinnon and Derickson 2012; Nelson 2014). Yet, the problematic articulation of resilience with capitalist processes and neoliberal ideals is historically contingent, not immutable or necessary (O’Malley 2010; Walker and Cooper 2011; Joseph 2013; Nelson 2014). Scholarship aimed at excavating this relationship by tracing the genealogy of resilience theory demonstrates that while resilience theory is vulnerable to co-optation, the possibility also exists to re-appropriate resilience thinking for more progressive and equitable ends (Nelson 2014). Resonating with Scott et al.’s (2013) argument in favor of recognizing resilience as a vital component water security, I argue that inclusion of resilience as an indicator of water security is also necessary to identify possibilities to buffer against increasing risk exposure. Following Beck’s (1994) Risk Society thesis, critical risk theorists have argued that the victories of capitalism and modernity, including technological progress and industrialism, are in fact contributing to increased risk, rather than diminishing it (Bulkeley 2001; Jarvis 2008; Klein and Smith 2008; Klein 2011).
The inclusion of responsibility as an indicator of water security has important implications for social and environmental justice and for rethinking possibilities toward more equitable futures. Drawing attention to the norms and institutions in place that structure the expectation and the enforcement of accountability help to bring into focus new solutions beyond traditional problem-solving approaches. Focusing on asking, identifying and naming who is responsible for exposure or harm and who should be held accountable for remediation serves to reframe the problem and thus reframe the solutions. Relations of power operate through the politics of responsibility to produce and reinforce categories of legitimacy and illegitimacy with implications for determining who deserves and is granted protection and conversely, for whom the obligation to intervene is framed as without merit and can be denied (Butler 2004; Secor 2007; Noxolo et al. 2012). Lauren Berlant (forthcoming) poses the question, “Is society organized for the flourishing of profit or for the prioritization of life?” Attending to ethical relations of responsibility and accountability shifts shared norms away from expecting responses that prioritize profit, toward instead demanding responses that prioritize life.

Methods and Study Site

Methods of Data Collection and Analysis

Data collection was conducted in 2013 and 2014 in the Sonoran-portion of the binational watershed. Semi-structured interviews and participant observation focused on agrarian activities in two ejido communities: Ejido Maria José Morelos and Ejido Emiliano Zapata (abbreviated to Ejido Morelos and Ejido Zapata). Interviews were conducted with sixteen participants, including ejido residents, ranchers, small-scale farmers, natural resource managers, and local politicians. Interview data and fieldnotes were coded to identify and organize informant responses on the
topic of water security, focusing specifically on access to adequate quantities of water of acceptable quality to support livelihood activities and indicators of strengthening or diminishing resilience in the local human and ecological community. Through this analysis of interview data and fieldnotes, a number of themes emerged: 1) impacts of increasing groundwater extraction by the mining sector on downstream water quantity; 2) impacts of heavy metal pollution from the mining sector on water quality; 3) uneven increases and decreases in riparian zone agriculture production across the different *ejido* communities; and 4) shifts in collective modes of grazing in the grasslands of the San Pedro watershed.

Groundwater well concession data was collected from the Mexican federal water agency CONAGUA and analyzed using geographic information systems (GIS) software to geocode and conduct spatial analysis of the point locations of the wells with respect to type of user, volume of concession, and maximum allowable depth of the well. A limitation of this data source is that the concession data is only a proxy measure for the well. Data about actual well pumping volumes and depths is not collected in the watershed and thus is not available. Using the concession data as a proxy introduces two possible types of error. First it is possible to over-estimate the number of actual drilled wells, the pumping volumes of the actual wells, and the depths that the wells have been drilled. Conversely, it is also possible to under-estimate these same metrics, as more wells may have been drilled than stated in the concessions, the wells may be pumping higher volumes of water, and may be drilled to deeper depths, due to the lack of regulation and oversight in the region.

Data on agricultural production and grazing subsidies was collected from representatives of Mexico’s Secretary of Agriculture, Ranching, Rural Development, Fishing, and Nutrition (SAGARPA, Spanish initials) and analyzed to determine trends over time and to corroborate data
from interviews with local producers. Finally, I collected additional data from published reports from *Grupo México*, the transnational corporation that owns and operates the *Buenavista del Cobre* mine located in Cananea, Mexico at the headwaters of the San Pedro River.

**Study Site**

The San Pedro River, a transboundary waterway originating in the mountains near Cananea, Sonora, Mexico cuts a long, narrow ribbon of verdant cottonwood-willow forest across the large, open grassland spaces of the Sonoran borderlands. Across the basin, highly variable precipitation and limited availability of surface water has led to steadily increasing groundwater withdrawals to meet the demands of the copper mining industry, irrigated agriculture, livestock raising, and urban population growth. Today, groundwater withdrawals, estimated at 89 cubic hectometers (estimated by the author through an analysis of groundwater concession data), far exceed the natural rate of recharge of 24 cubic hectometers per year reported by the Mexican water agency, CONAGUA. The upper San Pedro River basin receives between 300 to 750 millimeters of precipitation per year, with 65% of precipitation occurring between July and September during the North American Monsoon (NAM) season. The timing of the majority of precipitation during the summer season exacerbates water scarcity in the basin. The high rates of summertime potential evapotranspiration (PET), estimated at ten times the amount of annual rainfall in the lower elevations, reduce the amount of water available to naturally recharge the aquifer (Pool and Dickinson 2006). Recharge in the basin is also sensitive to El Niño Southern Oscillation (ENSO), which causes high interannual variability in winter precipitation. Principal recharge of the alluvial aquifer, which holds much of the available groundwater in the upper basin, depends on streambed infiltration and mountain front recharge (Pool and Dickinson 2006).
The San Pedro River riparian corridor - the narrow, forested zone of land adjacent to the stream channel - is an important site of agrarian production, for both grazing and agriculture activities, due to access to surface water and shallow groundwater. The riparian zone is also a critically important area for biodiversity conservation, providing unique forested and aquatic habitat for 84 mammal species, 14 fish species, and over 250 migratory bird species. In semi-arid regions, forested riparian corridors assist in controlling non-point source pollution, help to maintain cool water temperatures through shading, provide protection against flooding by attenuating peak discharge, especially important during NAM periods of intense seasonal precipitation, and play a key role in water infiltration and aquifer recharge (Bagstad et al. 2005; Ashraf et al. 2010; Forzieri et al. 2010; Wang et al. 2010).

Shifts in land use practices and water consumption produce significant impacts to dryland riparian systems. Fernandes et al. (2011) find that surface water extraction, groundwater pumping, grazing, nutrient inputs, and replacement of riparian forest with agricultural crops, can result in a loss of riparian habitat complexity, increased stand mortality and decreased growth rates, and impacts on the ability of species, such as cottonwoods that depend on seasonal flooding, to successfully reproduce. Importantly, the distributions of streamside plants, which comprise the structure vital for providing many ecosystem services, are dependent on numerous factors, including depth to the water table, rooting characteristics, and the riparian substrate geology, all of which are sensitive to the processes of land use change, including proximal agricultural and urban development (Amlin and Rood 2002).

Hydrologically, dryland riparian corridors, which exist in areas of discharge from the shallow alluvial zones of the aquifer where stream channels incise the top of the saturated zone, are characterized by tightly coupled groundwater and surface water dynamics. During periods of
low precipitation, baseflow, a natural discharge of groundwater, is a critically important source of water for producers who are dependent on access to surface water via canals and springs for agricultural irrigation and livestock production, the dominant rural economic activities. Baseflow, however, is highly sensitive to a number of factors, including season, vegetation dynamics, and groundwater pumping in wells located in close proximity to the river channel. Although average daily baseflow volume in the San Pedro River channel measures 19,900 m$^3$, the flow is highly differentiated based on season. For example, average winter daily baseflow volume is 35,750 m$^3$, while average daily June (pre-monsoon) baseflow volumes measure a mere 8,661 m$^3$/day (Pool and Dickinson 2006). The differences in access to water supply experienced by surface and groundwater irrigators are exacerbated during April – June, the months preceding the arrival of the North American Monsoon, which also corresponds to the hottest and driest time of the year. Water scarcity in the months leading up to the start of the summer monsoon severely restricts the ability of surface water-dependent producers to irrigate crops or provide feed for animals, leading to heightened vulnerability and often a loss of livestock to either early sales or death and the potential for crop failure.

Uneven Topographies of Water Security in the U.S.-Mexico Borderlands

Case 1: Mining Expansion and Riparian Zone Agricultural Production

Since the 1970s, groundwater demands in the Sonoran-portion of the San Pedro river have increased significantly due to rising production in Cananea’s Buenavista del Cobre copper mine (which contains an estimated 2-3% of the world’s copper supply), urban growth, and shifting agricultural and ranching practices. The expansion of production in the Buenavista del Cobre mine has driven aquifer exploitation in the region. From the middle of the twentieth
century (1945-1966), when annual groundwater pumping was estimated at 5.1 cubic hectometers, there has been an astronomic increasing trend to reach the 2013 high of 89 cubic hectometers of annual groundwater extraction calculated from the groundwater concession database (Figure 2). During the period between 2005 and 2007, water concession data show a particularly stark increase in new groundwater concession allocations (Figure 2). The data suggest that the San Pedro aquifer crossed a threshold, transitioning into a state of over-allocation, characterized by non-sustainable pumping, where discharge exceeds recharge with negative impacts on water table levels and the availability of baseflow, both crucial elements for surface water dependent agrarian producers and for the resilience of the riparian forest.

Furthermore, across the watershed, new groundwater wells for mining, urban consumption, and irrigated agriculture are being located in the alluvial recharge zone of the aquifer, along the main stem and tributaries of the river (Figure 3). This placement of wells of increasingly large volume and depth modifies the natural hydraulic connection between groundwater and surface water, with implications for timing and magnitude of streamflow downstream and non-linear reductions in the water table in the highly affected riparian zone.

The consequences of post-1992 neoliberal reforms in the agrarian sector in Mexico have rescripted previously communally managed ejido land as eligible for conversion to private property, and reforms to the Federal water law toward the privatization and commodification of surface and groundwater have contributed to a significant shift in the balance of power over riparian resources. The last twenty years has witnessed a massive transfer of control over land and water resources from small-scale collectives of agricultural producers and ranchers to the massive Buenavista del Cobre copper mine, the largest copper producer in Mexico and the third largest copper producer in the world, extracting multi-billion dollar annual profits from the
region. The mine is currently undergoing a 3.4 billion (USD) expansion with the aim to double its production capacity to 1.3 million tons of copper annually by 2017. This doubling of capacity will increase daily production from the current 90,000 metric tons per day to 200,000 metric tons per day, requiring substantial increases in water consumption, in particular the proliferation of deep, high-capacity groundwater wells in the riparian zone.

Industrial uses, primarily consisting of the Buenavista del Cobre mine, control 72.5% of groundwater concessions in the study area (64.5 hm$^3$). In stark contrast, agriculture controls 12% (10.68 hm$^3$), livestock production 0.5% (4.45 hm$^3$), and public urban supply 10% (8.9 hm$^3$) (Figure 3). An analysis of well depths also reveals a great disparity in access to deep groundwater supplies between production sectors. This disparity is most stark between the industrial sector (mining) and agriculture and livestock producers. The average depth of industrial well concessions is 352 meters, although allowable depths for some well concessions in the industrial sector reach 500 meters in vertical depth. In comparison, agricultural and livestock well concessions are far less deep, averaging 86 meters and 53 meters, respectively. Domestic wells for personal household use in the rural ejido population centers are the shallowest with an average depth of only 27 meters. Thus, the industrial sector has access to very deep supplies of groundwater, which serves to insulate mining and its economic profits from the negative impacts of water scarcity when groundwater levels drop and shallow wells become inoperative (Figure 5).

SAGARPA officials, charged with oversight of agrarian production in Mexico report that the dominant concern in the San Pedro watershed is drought. With no long-term climate stations in the watershed, outside of a private station in the mine with a speculated 100-year long record dating back to the turn of the twentieth century, measuring indices of drought is complicated.
However, for many producers, drought is not only interpreted as the lack of rainfall, but also as dry stream channels, inoperative wells due to the falling groundwater table, and increased mortality of grasses, cows, and the giants of the riparian zone, Fremont Cottonwood trees, which when mature can tower over 50 feet above the river’s surface. Referring to irrigated agriculture in the region, SAGARPA officials play a word game with the Spanish words for irrigation (iego) and risk (riesgo), illustrating the deep interconnections between water supply, necessary for cultivation in a semi-arid climate, and risk of losing one’s livelihood. To be dependent on irrigated agriculture in a drought-prone region with over-allocated water supplies is to be constantly exposed to risk of losing the viability of one’s livelihood.

Across the watershed, SAGARPA data reported at the municipio level, similar to a U.S. county, show a significant increase in total land area under cultivation from 385 hectares in 2008 to 918 hectares in 2014, a near threefold increase. Specifically, increases have focused on forage crops to support cattle, with alfalfa planting increasing from 75 hectares to 145 between 2010 and 2014 and green barley grass and green rye grass significantly increasing from 18 hectares in 2009 to 200 hectares in 2014 for barley and 40 hectares in 2008 to 240 hectares in 2014 for rye. Pasture land in good condition has been shrinking and increasing division of large tracts of land for common grazing have decreased as ejido parcels have become privatized and many have been sold to the mine for locating well fields. This has led to increasing demand from ranchers to buy supplementary feed for their cows, increasing their costs and leading to what one rancher called an era of forage scarcity (‘época de escasez de forraje’). Overall the cultivation of forage crops has increased from 356 hectares in 2008 to 828 hectares in 2014, representing 90% of the total agricultural cultivation in the watershed. Edible vegetable crops have increased from 29 hectares to 90 hectares over the same period (Tables 1-3).
Yet these increases aggregated to municipal scale belie stark differences between the experiences of agricultural producers in two *ejido* communities in the watershed. Increases in land under production have not occurred evenly, rather in certain areas, such as Ejido Morelos there has been an explosion of new areas under cultivation in the floodplain of the main stem of the river on the edge of the riparian corridor, just kilometers south of the international border. Here agricultural wells are some of the largest volume and deepest in the watershed (Figure 5). Thus, these wells and their owners are less likely to feel the direct impacts of surface water shortages and drops in the water table. Also, this location is far enough downstream from the mine to not be affected by the cone of depression that has formed under the mine’s well fields and the urban center of Cananea at the river’s headwaters. In contrast, agricultural production on Ejido Zapata has shrunk over the last two decades. Two factors have driven the decrease in production. First, Ejido Zapata is located in the headwaters of the watershed very close to the *Buenavista del Cobre* mine. As the mine has sought to expand its well fields, it has engaged in territorial strategies to either expropriate land holdings in the riparian zone or buy newly privatized parcels of *ejido* land to sink deep, large volume groundwater wells. Article 112 of the Federal Agrarian Reform Law states that *ejidal* and communal lands can only be expropriated for a public utility where the new social benefit will exceed the benefits of its current use. Riparian land being the highest value, due to the accessibility of water, has been prioritized as the first land to go through the process of parcelization and privatization as demand from the mine for control over this land is high. Thus, in some cases agricultural fields have been replaced by well fields for the mine. In other cases, people who try to continue farming find that it is no longer viable, because their shallow wells are affected by the cone of depression drawing down the groundwater table at a faster rate and are further inoperable once the mine’s deep wells are
turned on. In contrast to the deep agricultural wells in Ejido Morelos, the agricultural wells in Ejido Zapata are some of the shallowest in the watershed (Figure 5).

Utilizing the conceptual framework for water security I introduce in this article, an assessment of water security in the agricultural sector shows uneven exposure to risk and uneven capacity to cope with the shocks of water scarcity between different communities. In Ejido Morelos the distance of the community from the mine and the existence of deep wells serves to insulate the agricultural production sector from the scarcity produced by the mine’s high consumption of water. In Ejido Zapata, risk is high and resilience has been eroded leaving the local producers exposed to acute water shortage with little ability to cope and maintain land under cultivation (Figure 6). The indicator of responsibility is low across the watershed, as there is no expectation for accountability from producers, nor enforcement of accountability by the state for the mine’s unsustainable extraction of groundwater that is producing the regional water shortages. Thus, for Ejido Zapata, the measure of water security for the agricultural production sector is very low, while specifically for agricultural producers in Ejido Morelos water security is not recognized as a problem that is impacting their livelihood activities.

In the next section, I turn to an analysis of the collective ranching sector.

Case 2: Mining Expansion and Collective Ranching in the San Pedro Watershed

In semi-arid environments, cattle production necessitates very large tracts of land, as forage is limited. For example, a 1960 SAGARPA report states stocking rates of 16 hectares of land in good-condition per head of cattle. In the San Pedro watershed ejidos, established in 1959, the average ejiditario was given usufructory rights to 300 hectares of land, enough to graze approximately 18 head of cattle. Under these ecological conditions in semi-arid northern Sonora,
raising sufficient numbers of cattle for a viable livelihood required managing the large tracts of *ejido* land in common. It is important to note that common management of *ejido* grazing lands was often fraught with conflict (Sheridan 1996; Perramond 2010) and violations of *ejido* land tenure law were widespread. Prior to 1992, it was illegal to buy, sell, lease, or use *ejido* land as collateral for loans, yet previous research has found that these activities were common (Yetman and Búrquez 1998; Perramond 2008). In the aftermath of the introduction of PROCEDE - the 1992 constitutional reform that enabled the privatization and alienation of *ejido* land - there has been a shift in property relations away from commons management toward privatization. Yet, much of the rangeland in northern Sonora is neither economically nor ecologically well-suited for private title acquisition, due to the poor quality of the land (Perramond 2010). In areas with access to water and high quality forage, such as riparian zones and irrigated pasture, the years following PROCEDE has have seen an intensification of the fencing of land to demarcate parcels either undergoing or planning to undergo the PROCEDE process. This fencing boom has challenged the ability of the remaining *ejidatarios* to continue their practice of collective management and grazing of cattle over large, unimpeded tracts of land.

In addition to the challenges introduced by land tenure shifts under PROCEDE, decreasing quality of the grasslands has led SAGARPA to propose a carrying capacity of 28 hectares per animal unit, almost double the 16 hectare carrying capacity of the mid-1900s. In times of drought or poor seasonal rainfall, recommended hectares per animal can soar to almost twice the 28 hectares per animal, requiring nearly 50 hectares of non-irrigated grassland pasture to support one animal, creating a dire situation where grazing cattle without irrigated pasture and/or supplemental feed is no longer a viable option. During an interview with a SAGARPA official, our conversation turned to the condition of the pasture in northern Sonora. Following
nearly a decade of drought and stress from overgrazing, the land manager quoted statistics that 15% of non-irrigated pasture (*agostadero*) in the area is in critical condition, the lowest rating in their system. An additional 41% of pasture ranked in bad condition, leaving only 46% in regular or good condition. Based on ranchers’ self-reporting of cattle conditions to SAGARPA and the local ranching association, half of the cows are reported in good condition, but 20% are reported in critical condition, meaning they lack sufficient food and water, are very thin, and have a high chance of mortality.

In the context of this increasingly difficult cattle ranching landscape, there is an ongoing parallel shift in responsibility toward the devolution and individuation of responsibility for the health of cattle and the grasslands to each individual. This marks a change from previous collective forms of responsibility that held the community accountable for maintaining the health of their grazing livelihood. Referring to the grasslands of the San Pedro watershed as “the forage production landscape,” a SAGARPA official in a small adobe room lit brightly by the early morning Sonoran desert sun, listed possible solutions for the ranching sector to adapt to shifting social and ecological relations in the watershed. At the top of the list was a declaration that “the producer must be clear that his activity is business, with the goal of generating economic development.” A noticeable omission in our discussion of techno-scientific and capital-intensive solutions, such as increasing well depths, switching breeds of cattle, technification of pasture irrigation systems, was the lack of a mention of the decreasing availability of large tracts of land for common management and access to high quality forage and water in the riparian zone due to the ongoing processes of enclosure and privatization on the *ejidos*.

The establishment of the second generation of the Livestock Productivity Stimulus Program (PROGAN, initials in Spanish) in 2008 continues a long historical process of the
reorganization of cattle production along capitalist lines. State projects of modernization, specialization, and expansion of the livestock industry, especially targeted at cattle production in Sonora, have a long history dating back to the mid-twentieth century (Camou Healy 1998). The impacts of these projects have been particularly severe for small livestock producers and *ejidatarios* who have been inserted into the lowest and most risky entry points in the market economy. To survive, these small-scale producers have had to significantly reorient their livelihood strategies from heterogeneous to homogeneous economic activities, from subsistence farming of edible crops to exclusively cattle feed crops, and a full-scale integration of previously extra-economic activities into the market economy (Camou Healy 1998). PROGAN follows this trend contributing to a historical process of increasing individuation of risk and responsibility for collective and small-scale cattle producers.

The stated aim of PROGAN is to enhance natural resource conditions in livestock areas and boost productivity through sustainable planning, technology adoption, and improvements to grazing land, such as rotational grazing strategies and fencing parcels. Although the political aim of PROGAN appears neutral, Brenner (2011) notes that in practice it signals a significant shift in favor of private ranchers and serves to further erode the conditions of production faced by the collective ranching sector. First, to be eligible to receive monetary support through PROGAN, a producer is required to utilize a pasture rotation strategy. Rotational grazing is an intensive grazing strategy that requires fencing to be effective and is much more difficult to implement in collective management settings than by individual land managers. Thus the qualifying ranchland improvements privilege fenced parcels and private land managers over collective systems of continuous, extensive grazing (Brenner 2011). The articulation of pro-fencing policy in PROCEDE and PROGAN has led to a fencing boom across the state of Sonora and the San
Pedro watershed, more specifically. As a result, once open tracts of grazing land are becoming mazes of enclosures.

The PROGAN subsidy program offers differentiated levels of support for producers on a per-animal basis. Producers with 5 to 35 animals are eligible for a maximum support of $375 pesos/animal (~$30 USD/animal) while the maximum support offered for producers with more than 35 animals is reduced to $300 pesos/animal (~$23 USD/animal). Between 2012 and 2014, PROGAN subsidies received by the ejido communities in the San Pedro watershed decreased significantly, with drastic reductions between 2013 and 2014 (Table 4). According to SAGARPA records and interview respondents, this reduction is due to a shift in the PROGAN application that took effect in 2014. In 2012 and 2013, the ejidos applied for ranching improvement subsidies as a group, receiving one large payment per ejido. In 2014, the application process changed such that each individual raising cattle had to apply separately. This led to a major reduction in subsidies as only a fraction of the producers submitted applications, with just 28 individual applications from Ejido Vicente Guerrero, 32 from Ejido 16 de Septiembre, 34 from Ejido Emiliano Zapata, 36 from Ejido Ignacio Zaragoza, and 62 individuals from the most populous ejido, José María Morelos. This case suggests that contemporary shifts in agrarian law and policy in the Mexican-portion of the watershed lead to a privileging of neoliberal subjectivities. For example, ranchers operate with an incentive structure that encourages privatization. As a result, certain subjects have uneven access to state assistance and aid programs, access which is mediated by their willingness and ability to conform to neoliberal ideals of SES management, based on private property, the capitalization and financialization of natural resources, and individuation of responsibility.

Returning again to the proposed water security framework, the assessment of water
security in the collective grazing sector differs from that of the agricultural sector. Water security across the ranching sector is currently low. Risk is increasing and resilience is decreasing due to a number of intersecting factors: 1) the degradation of the non-irrigated pasture land; 2) the increase in fencing due to PROCEDE and PROGAN leading to a decrease of large tracts of forage and access to riparian zones for collective grazers; and 3) a shortage of water in livestock wells. These livestock wells tend to be the shallowest, which complicates the ability of ranchers to provide sufficient quantities of water to their cattle and decreases the ability of producers to cultivate irrigated pasture lands, a coping strategy recommended by SAGARPA officials. Yet, expectations and enforcements of responsibility do exist with the government offering subsidies and support programs, but increasingly these programs follow an individualized model that does not benefit collectives. Furthermore, programs such as PROGAN shift responsibility for maintaining the environmental conditions critical to ranching livelihoods away from collective decision-making toward the individual producer. Finally, the mine evades any expectation of accountability for its role in cutting up large tracts of grasslands and enclosing areas of the riparian corridor to install well fields.

**Discussion and Conclusions**

The over-allocation of groundwater in the San Pedro River aquifer has transformed SES relations in the watershed with evident material consequences. Yet, the impacts of the transformation have not affected everyone equally. Instead, pre-existing political-economic conditions, power relations, ecological dynamics, and historical differences in access to water supply serve to structure and differentiate experiences of water security and insecurity. In riparian SES, groundwater pumping is a key variable of system behavior due to its impact on
shallow groundwater tables, a critical source of water for human and ecological communities in semi-arid climates. In the shallow alluvial subflow zones of the riparian corridor, groundwater pumping is directly linked to local decreases in water table levels. As local water table levels drop, crisis conditions are experienced unevenly. Rather than affecting all sectors of production and human and biophysical communities evenly, producers who lack access to deep wells and vegetation species with shallower roots, such as the Fremont Cottonwood and Gooding’s Willow that comprise the riparian gallery forest, experience the most severe negative impacts.

The large *Buenavista del Cobre* mine utilizes large well fields with piped transfer schemes to move groundwater from the location where it is pumped (i.e. the riparian corridors of the local ejidos) to the location where it is utilized for resource extraction and processing. Paradoxically, the mining sector, which is pumping the largest amounts of water and significantly contributing to the production of water scarcity in the region and especially in the riparian zone, is also the best insulated from these same shortages through access to existing deep wells and the possession of capital to build new deeper wells if and when it becomes necessary. In contrast, local *ejido* residents, producers, and ecological communities who depend on shallow groundwater tables for their subsistence and survival are more likely to be exposed to the negative externalities that result from the steady expansion of capital accumulation in the mining sector.

Echoing Perrault’s (2014) case study of the Huanuni Valley of Bolivia, hydrosocial relations in the San Pedro watershed have also been profoundly reshaped by mining, with residents being increasingly separated from their means of production through processes of forceful alienation from the land and water resources of the riparian corridor. Moore (2015) extends this interrogation of novel strategies of appropriation and accumulation emerging from
new commodity frontiers. He draws attention to the accumulation of difference in these frontier spaces, where the accumulation of waste and toxification create different experiences and impacts of dispossession and conditions of precarity, differentiating between who accumulates surplus value and accumulates negative externalities (ie. waste, hazards, scarcity).

Under shifts toward neoliberal governance models, responsibility has undergone a significant reorientation from theoretically being the purview of a powerful state to provide for its subjects to an understanding of responsibility as being individually cultivated and internally regulated by each subject (Rose 2007). In the case of Mexico, this theoretical responsibility of the state to its citizenry has in practice been complicated due to the long history of political and economic liberalism that shaped subject-state relations, even in the decades following the 1917 Mexican Revolution, when agrarian reform and radical communal ideology was at its peak (Sanderson 1981). In Sonora, the implementation of PROCEDE and PROGRAN have created mechanisms for the re-privatization of access to land and water resources and encouraged private forms of ownership and individual management of resources. One result has been the further erosion of the remaining traces of collective resource management practices. The ongoing reorganizations of the social, political, and economic spheres in ejido communities under PROCEDE and PROGRAN are rescripting social and ecological relations within the watershed.

By naming and focusing specific attention on the uneven exposures and experiences of subjects to water insecurity, I aim to create new spaces of possibility to mobilize for more equitable water security futures in the riparian communities of northern Sonora. The water security assessment framework proposed in this article focuses on the interrelated indicators of risk, resilience, and responsibility in an attempt to open up avenues for creative solutions that, following Berlant, prioritize life, rather than profit. Seeking solutions that socialize and more
equitably re-distribute the negative effects of capitalist accumulation, such as aquifer depletion and the division of collective land holdings, the focus on accountability allows for creative thinking outside of capitalist profit motivations. For the San Pedro watershed, new solutions emerge by demanding that the mine be held accountable for the social-ecological system impacts of its activities. Re-investing even a small amount of the wealth extracted from the region back into the local community could fortify local water security. For example, Grupo México the owner and operator of the Buenavista del Cobre mine could be demanded to finance the construction, operation, and maintenance of a water treatment plant for urban Cananea and the design and construction of an integrated system of passive and active managed aquifer recharge, or risk losing its permit to operate the mine. The release of highly treated effluent into the riparian zone and the injection of it into aquifer in key sites has a high potential to remediate some of the water security challenges that the mine introduces into region.

The water security assessment framework I introduce aims to refocus the water security literature to attend to and explicitly account for the high variance of experiences of water security and insecurity at multiple scales between and within different livelihoods and economic sectors at a sub-watershed level. Utilizing the analytical framework to examine the two cases presented in this article reveals that the three social indicators (exposure to risk, ability to cope with disturbance, and expectation of accountability) have explanatory power. Coupled with the geographically specific dryland riparian ecological indicators, the drivers and contours of the uneven topography of water security and insecurity experienced across communities in the watershed are opened to analysis. A significant outcome of this type of water security analysis is to interrogate the causes, rather than the consequences of uneven water security, thus creating an opportunity to question dominant problem-framings and realize progressive solutions.
References


Camou Healy, E. 1998. *De rancheros, poquiteros, orejanos y crillos: Los productores ganaderos de Sonora y el mercado internacional*. El Colegio de Michoacan: Morelia, MX.

Derickson, K.D. and D. MacKinnon. 2015. Toward an interim politics of resourcefulness for the


Figure 1: Conceptual diagram of water security. This framework introduces three interrelated social indicators of water security (risk, resilience, and responsibility) nested within a set of ecological indicators. The inner and outer rings are connected through bi-directional feedbacks. In this case, the ecological indicators are specific to dryland riparian system functioning and are based on a set of indicators developed by the United States Geological Survey (USGS) for the San Pedro River riparian ecosystem.
Figure 2: Increasing aquifer exploitation over time, 1945-2013, Mexican-portion of the San Pedro River (Data Source: CONAGUA)
Figure 3: Map of the Mexican portion of the San Pedro River watershed. The red lines indicate private land holdings, the black lines indicate *ejido* land, and the black dots represent the locations of groundwater wells (Data Source: CONAGUA (Mexican well data) and Arizona Department of Water Resources (ADWR) (U.S. well data)). Map by author.
**Figure 4:** 2013 groundwater concessions by user, volume (cubic hectometer/year) and percentage of total concessions in the Mexican-portion of the basin (Data Source: CONAGUA)
Figure 5: Map of groundwater pumping concessions, by volume, depth of well, and sector of use. The map includes the location of the urban center of Cananea, the Buenavista Copper mine, the main stem of the San Pedro River (blue line), private land holdings (red lines), and ejido lands (communities that manage and cultivate land in common) (black lines). (Data source: 2014 Public Registry of Water Rights, CONAGUA). Map by author.
Figure 6: Water security assessment framework adjusted to reflect the conditions on Ejido Zapata for the agricultural sector. Water security is extremely low as risk is high, resilience is decreasing, and responsibility is low, with no expectation for or enforcement of accountability for the mine’s activities that are producing the water shortages experienced in the community.
Figure 7: Water security assessment framework adjusted to reflect the conditions for the collective ranching sector. Water security is low as risk is medium high and resilience is decreasing, but expectations and enforcements of responsibility do exist with the government offering subsidies and support programs, but increasingly responsibility for maintaining the environmental conditions critical to ranching livelihoods being individualized away from the collective-level to the individual.
Table 1: Total land area (ha) under cultivation, 2008-2014

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<th>2013</th>
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Table 2: Total crop production (ton) and price per crop ($/ton), 2008-2014 (Values are in pesos)

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<td>500 ($800)</td>
<td>540 ($900)</td>
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<td>2,800 ($842)</td>
<td>1,400 ($900)</td>
<td>1,260 ($874)</td>
<td>1,540 ($800)</td>
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Table 4: Annual subsidies received from PROGAN ranching improvement program, 2012-2014
(Data Source: SAGARPA)

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<td>520,987 pesos</td>
<td>443,025 pesos</td>
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<tr>
<td>Vicente Guerrero</td>
<td>467,362 pesos</td>
<td>397,237 pesos</td>
<td>178,360 pesos</td>
</tr>
<tr>
<td>16 de Septiembre</td>
<td>863,775 pesos</td>
<td>769,725 pesos</td>
<td>343,840 pesos</td>
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<tr>
<td>Ignacio Zaragoza</td>
<td>1,002,375 pesos</td>
<td>851,812 pesos</td>
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<td><strong>3,639,899 pesos</strong></td>
<td><strong>1,583,720 pesos</strong></td>
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</tbody>
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APPENDIX B

Social-Ecological Transformations in Riparian Zones: The Production of Spaces of Exclusion and the Uneven Development of Resilience in the Sonoran Borderlands

Lily A. House-Peters

1School of Geography and Development, University of Arizona

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Abstract

Overlaid with pipes, crisscrossed by barbed-wire fencing, and perforated by deep wells, watersheds in the Arizona (USA) – Sonora (Mexico) borderlands are marked by complex, overlapping political and environmental governance regimes. Riparian zones, characterized by accessible surface water and shallow groundwater, high quality forage, and nutrient rich floodplain soils, are highly valuable for a range of productive sectors, including agriculture, ranching, and mining. In the semi-arid, high-elevation grasslands of the binational San Pedro River watershed, access to water and riparian spaces is characterized by a long history of shifting political-economic conditions, changing natural resource management policies, and transformations in social-ecological relations. This paper examines the politics of transformation in riparian social-ecological systems (SES) in the Arizona-Sonora borderlands. The aim of this research is to advance understanding of the social and ecological struggles that accompany transformative moments in human-environment relations. I draw into conversation two influential, yet long separate, theoretical traditions found in political ecology scholarship. The research findings demonstrate that integrating a Marxist historical-geographical materialist approach to examining the mechanisms of riparian enclosure with a radical reinterpretation of social-ecological resilience theory serves to bridge a critical gap in understanding the complex relations between social-ecological transformation, the production of spaces of exclusion, and the uneven development of resilience in the borderlands.
Introduction

“Uneven development is the hallmark of the geography of capitalism...It is the geographical expression of the contradictions inherent in the very constitutions and structure of capital” (Smith 2008: 4)

On August 2014, the Buenavista del Cobre copper mine, owned and operated by the transnational corporation Grupo México, the third largest copper producer worldwide, with 2012 sales of over $10 billion, experienced a major tailings dam collapse. The resulting spill caused 40,000 cubic meters of toxic sulphuric acid and heavy metals to spill into the Rio Sonora River, which flows south from its headwaters in Cananea, Sonora, Mexico into Sonora’s capital city, Hermosillo. Following the spill, 22,000 people in seven riparian-zone towns situated along the course of the river were left without access to water. Exposure to the polluted water also proved devastating for livestock and agricultural operations, damaged the local riparian ecology, and caused wildlife mortalities. Hardly one month later in September 2014, the Buenavista del Cobre mine experienced a second spill, this time sending water contaminated with toxic tailings materials into the binational San Pedro River watershed (Figure 1). The San Pedro River flows north from its headwaters in the mountains near Cananea, traversing forty miles of semi-arid high elevation grassland before flowing across the international border into Arizona, USA. In light of the toxic spills, there have been calls throughout Sonora and beyond, echoes reverberating through the chambers of Mexico’s National Congress to the United Nations International Court of Justice, to cancel Grupo Mexico’s concession to operate the Buena Vista del Cobre mine in Cananea. However, the cancelation of the concession is highly unlikely due to the strong interrelations of economic and political dependence between Grupo México and the
Mexican state.

The recent consolidation of Grupo México’s power over land and water resources in the Mexican portion of the San Pedro River watershed represents a major reorganization of power relations in rural Sonora away from a previous emphasis on populist agrarian reform during most of the twentieth century. On February 4, 1959, an unusual delegation of high-level Mexican officials convened on the rural outskirts of Cananea, Sonora less than 100 kilometers from the U.S. border. Gathering on the Martínez Ranch, surrounded by the golden grasslands and forested riparian corridors of the San Pedro River and its tributaries, the President of Mexico, Adolfo López Mateos, the Governor of the State of Sonora, and the leaders of the nation’s Department of Agriculture stood before a crowd of hundreds. At noon, López Mateos, barely two months into his presidency, stepped forward to greet the assembled landless peasants, ranchers, agrarian reform leaders, and local mine laborers. In a brief speech steeped in patriotic prose extolling the revolutionary virtues of the 1917 Mexican Constitution, the President symbolically transferred 256,507 hectares (633,843 acres) of recently expropriated land to the people’s representative, Rubén Peralta y Peralta, for the creation of seven collective ranching ejidos (communities that manage and cultivate land in common) benefitting 853 formerly landless peasants. The expropriated latifundio (land privately-owned as a large estate), representing nearly the entire surface area of the Mexican-portion of the San Pedro watershed, had previously been under the exclusive ownership of the American mining and ranching magnate, Colonel William Greene and his heirs. During his sexenio (six-year presidential term), López Mateos distributed more land to the peasants than any president since Lázaro Cárdenas (1934–1940), a total of 30 million acres, signaling a period of strong state intervention in the economy (Sanderson 1981).
The expropriation of the American-owned Greene latifundio in the summer of 1958 and the subsequent reparto (redistribution) of the land to local campesinos (peasants) in early 1959 marked a watershed moment for the establishment of commons land management in the Sonoran borderlands. However, contemporary shifts in the political-economic and ecological conditions in the region have led to a series of acts of (re)enclosure. The term enclosure emerged from the sixteenth and seventeenth century process of creating boundaries using hedgerows to demarcate private property in the English countryside. Blomley (2007) defines the process of enclosure as the “conversion of commonable lands, whether on wastes, commons, or village fields, into exclusively owned parcels, and the concomitant extinction of common rights” (2). In agrarian systems of production, enclosure is closely tied to dispossession, though all forms of enclosure do not necessarily lead to dispossession. The enclosure and conversion of commonly managed land to private property serves to exclude certain users, thus divorcing certain agrarian producers from their means of production (i.e. land and water) (Blomley 2007; Hardt and Negri 2009; Linebaugh 2014). In the riparian zones of the San Pedro River, the experience of enclosure has been marked by the imposition of severe limitations to accessing surface and groundwater resources, fodder and forage materials for cattle, and nutrient rich, irrigable cropland (Figure 2).

In the binational San Pedro River watershed the dispossession and alienation of small-scale ranchers and farmers from land and water in the riparian zone via various mechanisms of enclosure have to a significant shift in the balance of power. In Mexico, neoliberal shifts in law and policy over the last two decades strongly favor the privatization of land and water resources. These shifts have chipped away at the ability of the ejidos and the ejidatarios (members of the ejido community) to maintain systems of common management of land and water resources, instead favoring industrial-scale mining operations and private capital-intensive agriculture. In
the Arizona portion of the watershed, the implementation of ecological conservation policies that exclude working landscapes, such as farms and ranches, serve to displace local producers.

In this paper, I trace the shifting politics of access to land and water in the Sonoran borderlands. This research reveals the effects of changes in political, institutional, and environmental management regimes on communities dependent on access to riparian resources. I identify distinct mechanisms functioning on both sides of the international border that result in the enclosure of riparian resources, unevenly restrict access to conditions of production, and produce landscapes of exclusion. In Sonora, I focus on changes in riparian relations in the decades following the 1959 redistribution of the Greene latifundio to create the seven collective ranching ejidos (Figure 3). Specifically, I interrogate the contested processes of privatization and expropriation attending to how these processes have affected the livelihoods of small-scale producers. In the Arizona-portion of the San Pedro River riparian corridor, I draw attention to the politics of conservation, illustrating the winners and losers of the creation of an exclusionary riparian conservation area in 1988 and demonstrating how conservation may become enrolled in programs of securitization in the context of increasing militarized US-Mexico border relations.

This research is guided by two main questions: 1) *What are the political-economic mechanisms through which riparian space is enclosed and certain actors become excluded from access to land and water resources?* and 2) *How do shifts in property rights regimes in the borderlands affect the transformation of human and ecological relations in the riparian zone of the transboundary San Pedro River?* To answer these questions, I draw on archival and field research conducted in the cities of Hermosillo, Mexico and Cananea, Mexico in northern Sonora and in Arizona, USA in 2013 and 2014. This chapter presents findings based on the analysis of primary and secondary sources, including land titles, agrarian records, policy papers, legal
documents, and newspaper articles and interviews with key informants (n = 25). Weaving theoretical insights from scholarship in Marxist political economy, political ecology and resilience theory through the empirics, I identify three mechanisms that serve to enclose riparian resources throughout the binational San Pedro River watershed. The mechanisms are: 1) privatization – the exclusive, alienable rights to land and water resources; 2) expropriation – the seizure of land and transfer of property rights to another individual or government entity; and 3) conservation – based on a western conservation logic of species-by-species habitat management that excludes human livelihood activities from occurring within the conservation area. The empirical evidence highlights the current shift toward limiting access to high-value land and water resources located within the riparian corridor and the consequences for the production of uneven resilience.

This chapter focuses on a specific, significant result of riparian enclosure in the *ejidos* of northern Sonora: the production of landscapes of exclusion. In the Sonoran-portion of the San Pedro River watershed, shifts in law and property rights regimes have chipped away at the power of the *ejidos* and the *ejidatarios* (members of *ejido* communities) to maintain their land in common. Recent legal reforms, for example the 1992 PROCEDE land reform and the updated Law of National Waters National, serve the natural resource exploitation needs of industrial capital through establishing legal precedent for the privatization of *ejido* lands and the legal separation of land and water. Research findings reveal that in Sonora, small-scale agricultural producers and ranchers are losing control over land and water resources as the *Buenavista del Cobre* copper mine’s power has increased rapidly in the region over the last 20 years. The world’s third largest copper producer, over the last 5 years the *Buenavista del Cobre* mine has rapidly increased copper production with concomitant requirements for access to greater supplies
of water at increasing depths from the aquifer (Figure 4). The mine is currently undergoing a $3.4 billion USD expansion with the aim of doubling its production capacity to 1.3 million tons of copper annually by 2017. This doubling of capacity will increase daily production from the current 90,000 metric tons per day to 200,000 metric tons per day, requiring substantial increases in water consumption, in particular the proliferation of deep, high-capacity groundwater wells in the riparian zone (Figure 5). The power wielded over resources today by the mine represents a major shift from February 4, 1959 when Mexican President López Mateos stood before a large gathering of peasants and agrarian reform leaders to create seven collective ranching ejido communities through the redistribution of the Greene latifundio land holdings.

The San Pedro River Riparian Corridor

In the San Pedro River riparian corridor—the forested floodplains adjacent to the river—there exist deep interrelations between riparian ecology, coupled with groundwater-surface water hydrology, and social institutions. Dryland riparian zone ecosystems are sights of both disproportionately high biodiversity and intensive human activity. These narrow bands of dense forest are significant biodiversity hotspots and provide a range of critical environmental services, including freshwater availability, flood protection, nutrient deposition, carbon sequestration, and groundwater recharge. Additionally, these resource-dense corridors support a wide range of crucial economic activities, including ranching, agriculture, mining, recreation, and tourism. Historically, in the water-limited Arizona-Sonora border region, the narrow alluvial floodplains along a river’s banks were one of few locations where irrigated agriculture was possible, resulting in a long history of social and ecological entanglements in these areas (Sheridan 1992).
In the riparian zone, biodiversity is critically dependent on hydrologic processes, specifically surface flow, shallow groundwater levels, and water quality. Existing in areas of discharge from the shallow alluvial zones of the aquifer where the stream channel incises the top of the saturated zone, riparian corridors exhibit strong coupling of groundwater-surface water hydrology. In these areas, the water table is high and vegetation can easily access groundwater, leading to dense canopies predominately comprised of cottonwood-willow forests and mesquite bosques. Water availability from surface flow and high groundwater tables are major determinants of riparian vegetation presence, diversity, and composition. The distribution of streamside plants is dependent on numerous factors, including depth to the water table, rooting characteristics, and the riparian substrate geology, all of which are sensitive to the processes of land use change, including nearby agricultural activities, resource extraction, industry, and urban development.

Hydrologic processes are influenced in complex ways by both direct human intervention and broader climatic and landscape-scale processes. The type and amount of water available in semi-arid region riparian systems varies by season due to influences from precipitation variability, recharge processes, and human activities that impact surface water diversion, groundwater pumping, and wastewater discharge. Additionally, land uses adjacent to rivers deeply impact riparian systems (Forzieri et al. 2010; Fernandes et al. 2011). For example, aquifer depletion, due to excessive groundwater pumping to sustain agriculture and urban development, reduces the amount and timing of water available to ecological communities in the riparian corridor. Surface water extraction, groundwater pumping, livestock grazing, nutrient inputs, and the replacement of riparian forest with agricultural crops, lead to a loss of riparian habitat complexity, increased stand mortality, and reduced ability of species to successfully reproduce.
Theorizing Uneven Resilience, Riparian Enclosure, and the Production of Landscapes of Exclusion

To elucidate social-ecological relations in the riparian corridors of the binational San Pedro River watershed, I draw into conversation insights from social-ecological resilience theory, political ecology and historical-geographical materialism. I argue that the explanation of socio-ecological transformation offered by traditional resilience theory (Holling and Gunderson 2002; Walker and Cooper 2011), although an increasingly pervasive logic in contemporary environmental governance and policy, is inadequate because it fails to elucidate power relations that impact coupled social and ecological dynamics. Instead, I introduce an approach informed by political ecology’s sensitivity to the operation of power and historical materialism’s grounded approach to understanding relations of property and political economy with a reinterpretation of social-ecological resilience theory. This integration of diverse theoretical approaches serves to bridge a critical gap in understanding the relationship between social-ecological transformations, the production of spaces of exclusion, and the uneven development of resilience.

Resilience theory presents a comprehensive framework for examining the ability of socio-ecological structures (SES) to absorb and withstand disturbance while maintaining existing SES and functions. However, there is a tendency for analyses formulated through resilience thinking (Walker and Salt 2006) to conceal, rather than reveal, politics and power relations. This tendency has led to descriptions of flat, static resilience landscapes, rather than recognition and further interrogation of variegated and uneven topographies of resilience within a single socio-
ecological system. Rich empirical scholarship in political ecology demonstrates that complex relations between natural resources and power intersect to shape differential, rather than similar, outcomes, in particular uneven access to natural resources within and between communities (Swyngedouw 1999; Ekers and Loftus 2008; Birkenholtz 2009, 2013; Bakker 2010; Sultana 2012; Budds and Sultana 2013).

Historical-geographical materialism understands human-environment relations as both historical and political, and importantly, as imbued with power. The historical-geographical materialist framework is useful for rethinking resilience through its grounded approach, which focuses attention explicitly on the “concrete historical and geographical conditions in which human action unfolds” (Harvey 1996: 8). Following this approach, I attend to the “connection of the social and political structure with production” (Marx 1977: 164) and argue for a central focus on processes of production. Denying the bourgeois argument that social processes follow natural, apolitical trajectories, the historical materialist argument instead employs political-economic analysis to reveal the mechanisms through which ‘changes in the land’ (Cronon 1983) have come to be. This type of analysis demonstrates how benefits and risks are distributed differentially both within and between groups of actors. The uneven distribution of benefits and risks is neither natural nor externally dictated, but rather internal to the system, a material representation of capitalism’s inherent contradictions. Following this approach, it is necessary to analyze social and political institutions that structure the conditions of production, which transform natural materials from use-value objects into commodities inhered with surplus value for market exchange.

It is through material processes that communities are conjured into being, set together or torn apart, and come to experience cooperation or conflict. Law and property are powerful
institutions that structure social and political relations between people and relations between humans and non-humans, through control over the transformation of non-human nature through processes of production. By recognizing the material basis of history, it is also possible to recognize that a certain mode of production is always combined with a certain mode of cooperation. For example, shifts in land and water property rights regimes affect how both social and ecological arrangements take shape, impacting which actors have access to the benefits provided by land and water resources and which actors are excluded. Thus, a historical-geographical materialist approach provides a useful analytical framework to examine social and ecological transformations in riparian spaces.

Transformations of raw materials via the production process engender socio-ecological transformations, famously coined by Neil Smith (2008) as the ‘production of nature’. The transformation of nature through human labor and technology is necessary to produce surplus value. Thus creating an entanglement between labor, value, property, and power. The emphasis on examining the conditions and processes of production brings property relations into focus. Property rights regimes represent a critically important factor in determining who has access to the benefits derived from natural resources, such land and water in semi-arid region riparian zones. Thus shifts in law, policy, and property rights serve to transform how actors experience space, as insiders or outsiders, included or excluded (Delaney 2001; Blomley 2008). Property is a powerful institution that creates, mediates, and maintains political relations between people (Macpherson 1978; Hurst 1964). Furthermore, property influences relations between social and ecological actors, through control over the transformation of non-human nature through labor and processes of production (Smith 2008). Shifts in law and policy that restructure property rights regimes, serve to redefine the rules, norms, and conventions that mediate access to the
benefits provided by land and water resources (Macpherson 1978; Yeh 2013). Property rights function as legally protected control over resources, which gives the property holder the power to make decisions over the allocation of scarce resources. This decision-making power renders property and property reform a thoroughly political issue (Hurst 1964).

I argue that enclosure serves as a useful theoretical framing device for understanding contemporary transformations in riparian spaces in the U.S.-Mexico borderlands. Through an examination of acts of enclosure, it is possible to link property rights, producers’ control (or lack thereof) over labor and the modes of production, and peoples’ experiences of dispossession and exclusion. In the century and a half since Marx’s writings on primitive accumulation, scholars have reworked definitions and understandings of the concept. For example, Alice Kelly (2011) offers an expanded definition, arguing that primitive accumulation is “neither simply accumulation via violent means nor a necessarily immediate process…it involves the act of enclosure of a commons, whether that be the enclosure of land, bodies, social structures, or ideas” (685). Thus, the process of enclosure of previously communally managed lands represents not only an economic shift, but also a transformation in socio-ecological relations and practices. Enclosure is not a monolith, rather enclosure can take different forms and can occur through various practices and mechanisms that introduce changes to processes of social reproduction and reproduction of labor power (Federici 2004).

In the San Pedro River watershed shifts in property rights regimes are restructuring the organization of access to, and management of, land and water resources in riparian spaces. Contemporary legal and policy shifts governing the management of land and water have created mechanisms for the re-privatization of access to riparian resources and encouraged private forms of ownership and individual management of resources, resulting in the enclosure of collectively
managed resources. The dissolution of the commons in favor of privatization and titling of land often leads to marginalization of smallholders and the poorest subsistence farmers (Yetman and Búrquez 1998; Assies 2008; Perramond 2008; Schroeder and Castillo 2013). Expropriation, the seizure of land and transfer of property rights, serves to re-structure social relations and power dynamics within and between communities, while the creation of protected conservation areas may remove land and water from productive activities in the name of ecological protection.

**Three Mechanisms of Riparian Enclosure**

In this section, I draw on the analysis of archival and interview data collected in Arizona and Sonora to illustrate how the processes of privatization (Section 4.A), expropriation (Section 4.B), and conservation (Section 4.C) have been deployed in the binational San Pedro River watershed to produce enclosures and spaces of exclusion in the riparian zone with significant implications for the production of uneven experiences of resilience across the watershed.

**Privatization**

The stark erosion of power of the agrarian reform sector began in earnest in the early 1980s, when the Mexican economy was marred by the 1982 financial crisis and the devaluation of the peso, followed by a phase of national debt restructuring programs and austerity measures. In 1991, citing the low productivity of *ejido* and other communally managed lands, Mexican President Carlos Salinas de Gotari introduced plans to transform the agrarian structure in Mexico, effectively ending a 70-year period of interventionist, state-led agrarian reform. The 1992 introduction of the Programa de Certificacion de Derechos Ejidales (PROCEDE), indicated a major shift in land tenure law and marked the transition to a period of market-led agrarian
reform (Perramond 2008). PROCEDE ended the redistribution of land for the creation of new ejidos and fundamentally altered land tenure laws. Previously, ejido land was considered usufruct property, meaning the right was only for the use of the land, not for full ownership. As such, ejido land was inalienable, signifying that the land could not be sold or rented (though scholarship points to widespread illegal renting of land and exchange of titles that occurred). PROCEDE formally initiated the process of legal certification and titling of parcels for privatization, transfer, and sale. The year 1992 also ushered in the implementation of the new Ley de Aguas Nacionales (Law of National Waters, LAN), which reformed the 1917 water law and significantly, conferred the ability to rent, sell, and transfer water right concessions, which was previously not allowed.

In the mid-1990s, the first stages of the PROCEDE process were carried out in the seven ranching ejido communities first formed in 1959. On October 9, 1994, the first PROCEDE meeting, titled the Assembly of the Delimitation, Destiny, and Allocation of Ejido Lands, was held in the ejido community of Emiliano Zapata. In addition to the ejido ruling body, consisting of the president, secretary, treasurer, and vigilance council, the meeting was attended by a visiting representative of the Agricultural Tribunal, a representative from the national census bureau (INEGI), a notary public, and 68 ejidatarios with legally recognized rights to common property. The order of the day was to vote on the ending of the regime of collective ranching, which would allow ejidatarios to obtain certificates for land tenure. The next step forward in parcel certification would be the official surveying and delineation of the boundaries of each parcel, which had to be recognized as correct by the voting members of the ejido assembly.

In nearby ejido Vicente Guerrero, the assembly of ejidatarios met in May 1995 regarding a solicitation by Minera María, located 10 miles west of the Buenavista del Cobre mine, to
purchase approximately 950 hectares (385 acres) of commons land (Figure 6) within the riparian corridor to install three new groundwater wells and a long-distance water transfer pipe. The open pit mine, owned by Grupo Frisco, a company within Mexican billionaire Carlos Slim’s holdings, stated that the land would be used for the construction and installation of processing plants and industrial installations, to continue the exploration and exploitation of mineral ores and to drill and install three wells. Originally, the mine began its operations in 1980 solely producing copper concentrates. However, the ability to expand operations to produce cathode copper (which began in 1999) required additional land, and more importantly, additional water resources.

The ongoing shifts in resource allocation from the collective management of the *ejidos* to the mining sector are marked by struggle and contestation. During a following general assembly meeting of *ejidatarios* of Ejido Vicente Guerrero on June 16, 1995, a conflict erupted regarding the mine’s solicitation pitting those who supported the mine’s plan against those in opposition. In September 1995 the case was transferred to the Agrarian Tribunal court in Hermosillo, the capital of Sonora. The trial, attended by 29 percent of the *ejidatarios*, heard arguments from a faction of community members who sought to challenge the allocation of land to the mine and called for the nullification of an earlier agreement that had been negotiated with the mining company. However, the judge, Maximiliano Figueroa Romero, decided against the protesting *ejidatarios* and Minera María eventually gained access to the land and the accompanying water resources. In 1997, the mine obtained concessions to pump 1,102 acre-feet of groundwater per year. Although this quantity of water is dwarfed by the 25,554 acre-feet per year (AFY) of groundwater concessions under the control of the Buenavista Copper Mine in Cananea (today owned by the multi-national corporation, Grupo México), it represents a significant strain on a
community already experiencing water scarcity, as the ejido now maintains rights to pump a mere 243 AFY, less than 5 percent of the total rights to groundwater in the local aquifer.

Previous research had clearly shown that groundwater pumping directly within the riparian corridor is strongly tied to local decreases in groundwater levels, leading to high mortality rates for cottonwood-willow forests (Stromberg et al. 1996; ADWR 2002; Lite and Stromberg 2005). The Gila River Adjudication determined that wells located in the subflow zone of the saturated floodplain alluvium significantly impact the quantity of surface water available in the river channel. Increasing demands for groundwater have caused the binational San Pedro River aquifer to become over-exploited resulting in significantly decreased groundwater levels. Stretches of the river that historically were perennial, meaning they contain water all year long, now only flow following precipitation events, and small lakes and ponds have experienced visible drying over the past decade as a result of the combined impacts of unsustainable pumping and long drought cycles.

In northern Sonora, a major outcome of the PROCEDE process has been the fencing of land to demarcate plots, although full privatization and certification of titles has been more limited. Importantly, these outcomes of the PROCEDE process are being implemented most intensely in the riparian zone. This is a result of the high value of riparian land, which is highly productive, especially for irrigated agriculture and animal husbandry due to access to surface water and the existence of shallow groundwater levels. The process of mapping and parcelizing land in the San Pedro River watershed has had the effect of rendering land tenure configurations increasingly visible (ex. fences) and legible (ex. maps and registered GPS coordinates) to the Mexican state. Yet, as the state increasingly attempts to make legible the dynamics and flows occurring on the surface of the land, the subsurface continues to elude this gaze. Rather, the
invisibility and opaque qualities of groundwater, including the difficulty of accurately modeling lateral flows within the aquifer, quantifying recharge and infiltration characteristics, and producing reliable maps of the aquifer’s piezometric surface remain persistent challenges and sources of great uncertainty in the San Pedro River.

In 2008, a ranching support program called PROGAN (Programa de Producción Pecuario Sustenable y Ordenamiento Ganadero y Apícola) was established with the aim of enhancing natural resources conditions in livestock areas by boosting productivity through technology adaptation and ranch improvements, such as fencing. PROGAN has served to reinforce the shift toward fencing land, which followed the implementation of PROCEDE. This articulation of PROCEDE and PROGAN has created a veritable fencing boom in the Sonoran borderlands. PROGAN disfavors ejidatarios ranchers in multiple ways. First, making the necessary improvements to grazing land to qualify for financial support through PROGAN is more feasible for private landholders with fenced parcels, than for those who remain part of grazing commons. Second, as fencing of land intensifies, collectively managing cattle becomes increasingly difficult, particularly in the Sonoran desert, where grazing capacity is one animal per 35 acres if irrigated pasture is not available and depending on climatic conditions. Once open tracts of grazing land have been transformed into mazes of enclosures, producers are denied access to water resources and highly productive forage in the riparian corridors.

**Expropriation**

The process of expropriation⁴ (colloquially defined as the taking of something from another’s possession for one’s own use) occurs when a public agency takes property, usually

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⁴ The legal definition of expropriation is “the compulsory taking from a person, on compensation made, of his private property for the use a public work” (Black 1910).
land, for a purpose deemed to be in the public interest. In the case of Mexico, expropriation has taken both politically progressive and regressive forms. The expropriation and subsequent redistribution of the Greene *latifundio* in the late 1950s was an example of a politically progressive expropriation that benefited hundreds of landless peasants and wage laborers.

However, in the late 1980s and early 1990s, as the *Compañía Minera de Cananea, S.A.de C.V.* looked to expand and intensify copper production at the *Buenavista del Cobre* mine, increasing access to water resources to enable increased concentration activities in the mine became a paramount concern. Prior to the 1992 agrarian reforms, that introduced the PROCEDE process allowing the parcelization and privatization of collective *ejido* land, discussed in the section above, the mine looked to the Mexican state to utilize expropriation as a strategy to gain access to specific desirable territory within the San Pedro watershed, classified as *ejido* land, and thus not available for sale. The political influence and intimate entanglements of the leadership of the mine with government leaders in the State of Sonora and beyond, echoing through the halls of the federal government in Mexico City, empowered the mine to seek state expropriation of *ejido* lands via the justification of serving the greater public interest.

In 1990, an articulation of multiple political and economic factors created the conditions to serve the mine’s interests for expansion. Against the negative perception of *ejidos* as wasteful, and characterized by low productivity, the mine took on the image of high economic productivity and profit potential. During the 1980s, the agrarian sector lost political capital, a trend that was further cemented by the rise of a neoliberal climate within Mexico under President Carlos Salinas de Gortari. Further, because the *ejidos* depended on a system of usufruct property rights, which remained the actual property of the Mexican Federal government, expropriation of these lands was arguably less difficult than for private property rights. Thus, in the years preceding the
period of privatization, expropriation was utilized as a revanchist strategy for the mine to (re)gain control of land for access to the groundwater resources beneath located within ejidal territory boundaries. The consequences of expropriation cases in the San Pedro River were the enclosure of commons grazing land and high value land within and along the riparian corridor.

On November 5, 1990, a presidential decree ordered the expropriation of 566 hectares (1,400 acres) of commons grazing land from the territory of Ejido Emiliano Zapata for use by Minera de Cananea, (the Cananea Mine company) (DOF 1990). The Comisión de Avalúos de Bienes Nacionales (Commission of National Asset Evaluation) assigned a value of $1,018,275 (Mexican pesos) per hectare of expropriated land, equivalent to approximately $345 (USD) due to extreme inflation in Mexico in 1990. The decree justified the expropriation of the land under Article 112 of the Federal Agrarian Reform Law, which states that ejidal and communal lands can only be expropriated for a public utility where the new social benefit will exceed the benefits of its current use. On May 7, 1991, the expropriation was finalized during an official meeting held in Hermosillo, Sonora. The meeting, attended by engineers from the Agrarian Delegation of the State of Sonora, a representative from the National Bank of Works and Services (Banco Nacional de Obras y Servicios), and a lawyer from the Cananea mine, formalized the measurement and demarcation of the boundaries of the expropriated land and transferred the compensation payment to the ejido’s general fund.

Simultaneously, an additional presidential decree on November 6, 1990 ordered the expropriation of 639 hectares (1,579 acres) of grazing and agricultural land from Ejido Cananea in the location of the Ojo de Agua, the area understood by local residents to be the water rich initiation point of the San Pedro River (DOF 1990). The land to be expropriated bordered two earlier smaller expropriation sites, an 8 hectare area expropriated on December 24, 1980 in favor
of the Federal Electricity Commission to be used for the construction of the substation of Cananea, a source of electricity critical to the mine’s operations. The second expropriated parcel was a 21-hectare area transferred from the Ejido Cananea to the mine on July 20, 1988 for the construction of an industrial park. The additional 639 hectares expropriated in 1990 at the Ojo de Agua site were valued by the Comisión de Avalúos de Bienes Nacionales to be worth a unit value of $600,750 pesos per hectare of pasture land, a mere 59% of the value estimated for the collective pasture land cited in the presidential decree for the Ejido Emiliano Zapata expropriation published the day previous. Thus, for the 639 hectares of Ejido Cananea pasture land, in arguably one of the most water rich areas of the river’s headwaters, the ejido was offered the equivalent of $130,068 US dollars, $65,000 less than for the collective pasture lands expropriated from Ejido Emiliano Zapata. The reason for this disparity in valuation remains unclear in the historical documents located in the archive, but is especially curious given the location of the Ejido Cananea land to develop the water resources of the Ojo de Agua site. The text of the expropriation documents focused solely on land resources, agostadero (non-irrigated pastureland), in particular, demonstrates how access to water, the actual object of these negotiations, is elided and hidden under a discourse and legal regime based on control over land. The expropriation of these relatively small areas of land, under 1,000 hectares, is distinct from mining expansion in other areas, where expansion is land-based, rather than water-based. In the San Pedro, the control of these small parcels of surface area, enabled control over large magnitudes of sub-surface water resources, necessary for the expansion of the mine’s copper concentration activities, the most water-intensive step of the copper mining process.

Conservation
In the 1980s scientists measured rapidly declining groundwater levels of 1-2 feet per year in Southern Arizona, which were linked to declining surface water flows in the San Pedro River. As a response to pressure from environmental agencies and as an attempt to mitigate widespread environmental degradation in the riparian corridor, in 1988 the U.S. Congress designated a 40-mile conservation area in the Arizona-portion of the river. Within the boundaries of the San Pedro Riparian National Conservation Area (SPRNCA) agrarian activities were eliminated, explicitly creating a zone of exclusion for livestock grazing and agricultural production. Previous to the creation of the SPRNCA and the transfer of the ownership of the land to the Bureau of Land Management (BLM), the 43,000 acres of San Pedro property was part of the historic, sprawling San Juan de las Boquillas y Nogales and San Rafael Del Valle Spanish land grants, dating back to 1827. These land grants changed hands on multiple occasions during the 161 years between 1827 and 1988, at times owned by Colonel William Greene, comprising the headquarters of Greene’s massive Cattle Company operation, later owned by William Randolph Hearst and his Kern County Land and Cattle Company, and from 1971 to 1986, the date of the exchange with the BLM, owned by the Tenneco Oil company. Throughout these changes of ownership over the land, cattle grazing remained the primary activity. Following the dissolution of Greene and later Kern County’s large cattle operations, Tenneco leased the land to ranchers for free-range grazing operations. For example, in 1986, when the BLM acquired the land, about 4,000 cattle were being raised on the 197,000 acre Little Boquillas ranch, headquartered at Fairbanks, Arizona. With the transfer of the land from Tenneco to the BLM in exchange for a 40,947 acre property of undeveloped public land west of Phoenix, commenced a moratorium on grazing, which impacted ranchers leasing land across the Boquillas and Del Valle ranchlands, who had previously leased grazing lands from Tenneco.
The designation of the SPRNCA further fragmented an already internationally divided riparian space, establishing asymmetrical land management practices on either side of the border; as part of the river flowing through Arizona was designated a ‘livestock-free’ landscape, while open-range cattle grazing and livestock production continues in Sonora. Kelly (2011) contends that conservation serves as a mechanism for the ‘legalized seizure’ of property in the form of protected areas. Powerful narratives that privilege the conservation of wildlife and natural resources over the livelihood needs of local groups serve to legitimate the creation of a particular model of protected area. In the case of the SPRNCA, the exclusion of cows is a technology of government founded on a very particular understanding of nature based on expert discourse and Western understandings of conservation science. This understanding of nature as a system external to humans, with an internal equilibrium that has been thrown off balance, allows for environmental policy decisions that restrict certain subjects from having access to natural resources, under the justification that conservation through exclusion of livelihood activities is the only method that can reestablish the system to an “original state” of equilibrium.

Furthermore, the role of the BLM, the designated manager of the SPRNCA, has recently begun to shift. Although an original task of the BLM was to manage and monitor the trespass of cattle in the SPRNCA corridor, this role has transitioned to include the management and monitoring of migrants who pass through the SPRNCA, which is a major travel corridor. Where cattle were originally considered the largest threat to environmental conservation in the riparian zone, monitoring the movement of migrants through the corridor is increasingly part of BLM activities. The Southern Arizona Project (SAP) and Operation Restore Our Arizona Monuments (ROAM) are on-going efforts by the BLM to address the impacts of illegal immigration and drug smuggling on public lands in southern Arizona. Operation ROAM establishes a partnership
between the BLM and the U.S. Border Patrol, the Alliance to Combat Trans-National Threats, the Arizona Department of Public Safety, and local County Sheriff’s Department. BLM’s 2011 SAP report states that Fiscal Year 2011 marked a major shift in the emphasis and approach of the BLM toward the management of border issues through the expansion of Operation ROAM. This marks a transition of BLM activities from being mainly reactive clean up and restoration activities to proactive tactics to monitor migrants moving through the riparian corridor. Operation ROAM is described as a resource protection and restoration program with the goal of “enhancing the protection of natural and cultural resources on public lands and improving coordination and cooperation with border law enforcement and land management partners” (BLM 2011: 1). To meet these goals, the BLM Arizona Rangers partner with other law enforcement officers for two-week periods as part of law enforcement ‘surges.’

Thus, the shifts to conservation and more recently securitization, based on the logic of exclusion, has enrolled new actors and agencies in riparian management and served to rescript power relations in the region. Where ranchers had long enjoyed a privileged position, the new politics of exclusion in the SPRNCA have shifted privilege away from ranchers to land management agencies, urban residents, recreationists, and military and border security forces. Under the justification of regional economic growth, ecological conservation, and border securitization, the riparian zone of the San Pedro River has become a corridor of exclusion and an object of the state’s scrutiny.

Discussion

The cases examined in this chapter illustrate the development of increasing inequality in power-relations in the riparian spaces of the San Pedro River watershed in northern Sonora,
Mexico and southern Arizona, USA. Transformations in the political economic and ecological conditions in the borderlands led to restructuring of property rights regimes for productive natural resources, such as land and water. In Sonora, Mexico, following the 1992 land and water law reforms, there has been a re-consolidation of groundwater resources under mining company control. Access to very deep supplies of groundwater serves to insulate the industrial mining sector and its economic profits from the negative impacts of water scarcity when groundwater levels drop and shallow wells become inoperative.

In contrast, local rural residents, agricultural producers, and ecological communities who depend on shallow groundwater tables for their subsistence and survival are exposed to the negative externalities that result from the steady expansion of capital accumulation in the mining sector. In *Changes in the Land*, Cronon (1983) demonstrates the critical importance of interrogating the social and ecological processes that shape transformations in material conditions. His investigation of the introduction and subsequent penetration of private property and capitalist relations in the U.S. colonial period provides a useful, though historically and geographically distinct, case of how the transition from a subsistence economy to capitalism served to alienate both the products of the land and the products of human labor. This process resulted in profound transformations in both human and more-than-human communities across the eastern U.S. seaboard. The case of northern Sonora I present in this chapter shares certain common contour lines to Cronon’s case. In particular, it is evident across both cases that shifts in property regimes are key to these political-economic transitions. Specifically, the social reorganization that accompanies the move from a claim to the use of things on the land (i.e. usufructory rights) to a claim to the land itself (i.e. private, alienable rights), serves to erode
social obligations and to deny the possibility for collective solutions in favor of solutions that support individualistic, permanent, alienable, and exclusive rights to resources.\(^5\)

Policies that promote individualized decision-making and surplus-profit motivations result in the increased success of certain actors at the expense of others. For example, the industrial mining sector has access to very deep supplies of groundwater, which serves to insulate mining and its economic profits from the negative impacts of water scarcity when groundwater levels drop and shallow wells become inoperative. In riparian SES, groundwater pumping is a key variable of system behavior due to its impact on shallow groundwater tables, a critical source of water for human and ecological communities in semi-arid climates. Thus, as local water table levels drop, crisis conditions are experienced unevenly. Previous research in agrarian landscapes argues that enclosure often serves to compound rather than alleviate grazing problems for communities and ecosystems (Yeh 2013). The exclusion of individuals and communities from accessing land and water resources necessary for maintaining their livelihoods has serious negative implications. Examining the intersections of water management and property rights regimes with social relations, political economy, and ecology exposes concealed sites where the contradictory dynamics of capitalist accumulation penetrate systems of natural resource production. This approach also illuminates how these processes produce subjects differently excluded from the benefits of natural resources, especially land and water.

**Conclusion: Towards a Socio-ecological Approach to Management**

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\(^5\) Property theorist C.B. Macpherson (1978) proposes a rethinking of property away from the confined understanding of “the right to exclude others from the use or benefit of some thing” to a more just understanding of “an individual right not to be excluded by others from the use or benefit of something” (201).
This paper has examined how shifts in property rights regimes intersect with social and ecological transformations in riparian spaces in the binational San Pedro River watershed leading to uneven outcomes for producers in the region. As the art of governance continues to shift in favor of neoliberal strategies for resource governance, vulnerability to and responsibility for coping with hardship are being transferred from societal-level concerns to individual obligations. Scholars of neoliberalism point out that individualized, market-based solutions come to appear in lieu of collective political solutions and that the ideal of the fundamentally self-interested individual comes to limit the sense of what is politically possible (Brown 2006; Read 2009).

Processes and events that reconfigure social-ecological power relations often result in the exacerbation, rather than the amelioration of difference and marginalization. Lefebvre (1991) argues that “the dominant form of space, that of the centers of wealth and power, endeavors to mold the spaces it dominates, and it seeks by violent means, to reduce the obstacles and resistances it encounters there” (49). Transformations of social-ecological relations thus serve to differentiate individuals and communities vis-à-vis access to natural resources. The contradictions inherent to capitalism are expressed in the production of spaces of exclusion whereby some bodies and ecologies are unevenly exposed to scarcity, vulnerability, and harm. Said another way, “contradictions in the social relations entail social contradictions on the land” (Harvey 1996: 185). Thus, attending to modern forms of enclosure, exclusion, and dispossession provides new, and necessary, avenues of critical research into social-ecological transformation and social and environmental justice in landscapes of resource conflict. This intervention unlocks new conceptual avenues for proposing forms of management that socialize and more equitably redistribute the negative effects of capitalist accumulation, such as falling water tables and aquifer depletion.
Scholars of human-environment geography argue that in addition to the recognition of power and politics as central to resource struggles, ethics must also be explicit for resource management to achieve success. While some scholars call for the development of an ethic of human solidarity that transcends social divisions and instead recognizes commonality in the human experience (Linebaugh 2014: 140), post-humanist inspired scholars, such as Braun (2002), draw attention to the need for an environmental ethic grounded in the inescapable entanglement of human and nonhuman bodies and objects (c.f. Aldo Leopold). A return to thinking about ethics provides new ways to imagine reconciling conflicting interests and reviving strategies of collective resource management. Rather than eliding and ignoring social and ecological difference, it is imperative to recognize and value the multiple perspectives, interests, and knowledges present in riparian zones. In contrast to laws, policies, and practices that manage through exclusion, I argue that management approaches based in an inclusive environmental ethic may open new political possibilities. Approaching the relations between diverse human communities and the multiple nonhuman entities that exist in riparian systems as webs of intricate relations, impossible to disentangle, it becomes possible to locate affinities, cultivate solidarity, and build coalitions across social and ecological boundaries. An approach based on coalitions and cooperation creates opportunities to move beyond contentious narratives and assignations of blame toward management decisions grounded in collective responsibility in opposition to the individualist ontology of risk management presented by neoliberal environmental management models. Furthermore, instead of dedicating attention solely to economic growth, which favors unsustainable industrial-scale mining and agriculture with little regulation, a social-ecological approach sensitive to a post-humanist ethical approach takes
seriously broader social and environmental considerations, including social reproduction and health and well-being for both human and non-human communities.
References


Birkenholtz, Trevor. “‘On the Network, Off the Map’: Developing Intervillage and Intragerder


Figures

Figure 1: Map of the binational San Pedro River watershed. (Figure created by Author. Data Source: San Pedro River Basin Data Browser).
Figure 2: (Left hand photo) Forested riparian zone of the San Pedro River during the summer monsoon season (July-September), when the region experiences heavy seasonal precipitation (Photo by author, July 2014); (Right hand photo) Agricultural field adjacent to the riparian corridor in Ejido Emiliano Zapata (Photo by author, March 2014).
Figure 3: Map of the Mexican-portion of the binational San Pedro River watershed, depicting ejido property boundaries (black lines) and private property boundaries (red lines). (Figure created by Author. Data Source: San Pedro River Basin Data Browser).
Figure 4: Graph of the relation between increasing copper production at the Buenavista del Cobre mine in Cananea, Sonora and increasing groundwater exploitation since 2010. During the years 2008-2010, laborers at the mine were on strike, effectively halting copper production for two years before the Mexican government broke the strike using the deployment of the Mexican National Guard in June 2010. (Data Sources: Mexico CONAGUA Agency REPDA database; Grupo México Annual Reports to Investors)
**Figure 5:** Groundwater well concessions for the Mexican San Pedro, represented by type and size of use (left-hand map) and by well depth (right-hand map). (Figure created by Author. Data Source: Mexico CONAGUA Agency REPDA database)
Figure 6: Privatization and sale of riparian land and water rights to Minera María from an ejidatario-turned private landholder in Ejido Vicente Guerrero. (Photo by author, May 2014)
APPENDIX C

Uneven Conservation of Binational Riparian Resources: Institutional Conflict, Ecological Uncertainty, and Community Organization

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For Submission to Society and Natural Resources

Abstract

Effective natural resource management and ecological conservation in transboundary watersheds remain significant challenges worldwide. This paper presents a comparative study of two attempts, one successful and one unsuccessful, to establish riparian conservation zones in the transboundary San Pedro River watershed, spanning the border of Arizona, USA, and Sonora, Mexico. This paper utilizes a social-ecological system framework, developed by Elinor Ostrom, to examine how multi-scalar institutional networks, the participation of diverse actors and grassroots organizations, and complex riparian-zone ecology articulate to produce uneven conservation policies for protecting riparian resources. To advance understanding of the socio-political and ecological factors significant to riparian conservation in a binational context, the study reconstructs the institutional and environmental histories of two riparian conservation planning efforts in the binational San Pedro River. Research findings from the comparative analysis elucidate four key factors that contribute either to the success or failure of attempts to establish conservation areas in binational riparian corridors: 1) legitimacy and authority of competing sources of ecological knowledge; 2) misalignment and dissonance within multi-scalar institutional networks; 3) community politics and inter-group alliance formation; and 4) the level of correspondence between policy discourse and local material concerns. The findings challenge broad, theoretical approaches to transboundary conservation, instead shifting attention to the particularities of multi-scale interrelations and interdependencies between actors, institutions, and ecologies in riparian socio-ecological systems.
Introduction

Worldwide, the effective and equitable management of transboundary watersheds and ecosystems – hydraulically and ecologically connected systems that traverse national boundaries – presents a significant challenge to natural resource governance. Implementing conservation of sensitive transboundary resources, such as biodiversity hotspots, surface and sub-surface water flows, and migratory land and air routes for endangered species, represent highly contested processes that often end in inequitable or unsustainable outcomes (UN 2009). In transboundary riparian social-ecological systems (SES) – the forested floodplains adjacent to the river channel – hydrologic flows and biophysical ecosystem dynamics defy national political borders and boundaries. Riparian zones are characterized by tightly coupled groundwater-surface water interactions. The biophysical and geohydrological complexity of riparian SES magnifies the already significant challenge of achieving effective transboundary resource management. Riparian SES overflow the boundaries between land and water, instead demonstrating permeable movement between forest canopy biomass, surface water flows, and groundwater levels. Yet management regimes remain bounded and asymmetric, producing a tapestry of interwoven, overlapping, and at times contradictory, rules, rights, and resource extraction and conservation practices. Thus, the interdependence of land and water systems in riparian SES poses serious challenges to previous management regimes, which have relied on separate governance structures for land resources, surface water, and groundwater, rather than holistic conjunctive management approaches.

The establishment of integrative and collaborative natural resource management — especially in transboundary contexts — is challenged by the existence of multiple agencies and organizations with distinct management priorities, jurisdictions of authority, public cultures of
legitimacy and compliance, and political-economic realities. In the US-Mexico border region, previous research has found a number of additional factors that serve to further complicate transboundary collaboration for natural resource management (Browning et al. 2004; Wilder et al. 2010; Varady et al. 2013. These factors include a long history of contestation over water distribution, unilateral decision-making, institutional asymmetries, uneven topographies of power relations, distinct historical contexts and systems of property relations, diverse natural resource management ideologies and distinct conservation ethics, multiple, competing demands for resource use, distrust between actors, and uneven access to information about the social and biophysical characteristics of the natural resource system (Browning et al. 2003; Milman and Scott 2010; Megdal and Scott 2011; Ruiz et al. 2011; Browning and Perla-Pliego 2011).

Institutions – the formal and informal rules and practices that guide human decision-making – serve a crucial role in mediating human-environment relations, both shaping human behaviors toward natural resource extraction, consumption, and disposal, and reshaped by the environmental feedbacks experienced (Ostrom 1990; North 1991). Scholarship from the fields of natural resource governance and institutional analysis draws explicit attention to the rules and actors that affect resource access, use, and decision-making. Achieving effective and equitable conservation of common pool resources (CPRs), such as riparian corridor resources, requires shifts and even transformations in institutional conditions. Insights from the literature reveal that institutional change is a deliberative, contested, and messy process that draws diverse actors, organizations, and ecologies into network structures and webs of relations (Bromley 1989; Schlager and Ostrom 1992; Bruns and Meinzen-Dick 2000; Conca 2006; Ostrom 2007; Sick 2008; Young 2010; Heikkila et al. 2011; Epstein et al. 2013; Vogt et al. 2015).

Elinor Ostrom’s well-known, robust SES institutional analysis frameworks presents a
common framework and diagnostic method to organize empirical data into a nested, multi-tier system of variables to identify specific interactions and resulting outcomes in the context of managing CPRs within complex SES (Ostrom 2005, 2007, 2009, 2011; McGinnis and Ostrom 2014). For Ostrom (2009), SES are “composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc” (419). The SES framework emerges from a rich body of existing empirical case studies of CPR management in ecosystems and communities situated in locations across the globe. Rather than imposing a false separation of natural and social components in a system, the SES framework recognizes that these components constitute a single system, characterized by feedbacks between nature and society across multiple temporal and spatial scales. Although a large corpus of empirical scholarship on CPR management exists, scholars indicate a need for additional comparative studies. Specifically, studies that identify and analyze the variables at play in successful and unsuccessful attempts to establish collaborative natural resource management and conservation in transboundary resource contexts from a perspective sensitive to both biodiversity and the maintenance of local livelihoods (Browning-Aiken et al. 2004; Diaz-Caravantes and Scott 2009; Petursson et al. 2011; Suhardiman et al. 2012; Eckstein 2013; Varady et al. 2013).

Drawing on Ostrom’s SES framework (Ostrom 2007, 2009; Ostrom and Cox 2010; McGinnis and Ostrom 2014), this research aims to answer two questions. First, which socio-political and ecological variables (using the language of Ostrom’s SES framework) drive the success or failure of establishing and implementing riparian conservation in a transboundary watershed? Second, how do the interactions of these variables within the same watershed ecosystem but across different social, economic, and political settings impact the outcomes of
riparian conservation? Through an institutional analysis of two historically intertwined case studies, we identify, compare, and characterize the relevant social and ecological variables and their interactions associated with successful and unsuccessful riparian zone conservation outcomes in the transboundary San Pedro River watershed (Figure 1), spanning the US-Mexico border. Specifically, the article compares and contrasts factors that led to the successful establishment of a riparian conservation zone in the US portion of the river, in 1988, known as the San Pedro Riparian National Conservation Area (SPRNCA); and the failure of subsequent deliberations to establish the Mavavi nationally protected area, an expansive conservation reserve in the Mexican portion of the watershed including the riparian zone and surrounding valley and mountains, during the period 1997-2003.

Our central argument is that distinct articulations of similar SES variables served to produce the establishment of uneven riparian zone conservation policy outcomes in the U.S. and Mexican portions of the transboundary San Pedro River watershed. From our comparative analysis of the significant variables involved in the establishment of the SPRNCA in 1988 and the failure to establish the Mavavi in 2004 emerge four interrelated factors that we argue help explain the outcomes of riparian conservation deliberations in a transboundary region. The first factor legitimacy, uncertainty, and authority of competing sources of ecological knowledge attends to the level of knowledge sharing, sources of knowledge, information flow, trust, and the degree of certainty in the knowledge characterizing the hydro-ecological system. The second factor misalignment and dissonance within multi-scalar institutional networks concerns the political process, including asymmetries present in legal and regulatory frameworks across geographical boundaries, the scale at which formal deliberations are taking place, and who holds positions of political power in the deliberations. The third factor community politics and
**intergroup alliance formation** accounts for the multiple interests present, how interests of different parties intersect or contradict each other, and which groups are active in civil society and less formal settings, such as local community meetings. The fourth factor **level of correspondence between policy discourse and local material concerns** examines the degree of understanding about the social, economic, and ecological concerns of local communities, the process of conceiving and implementing policy, and who controls and legitimates discourse.

This research makes three important contributions to the natural resource management scholarship. First, we contribute empirical data to the larger scholarship of CPR management in transboundary contexts. This evidence-based approach serves to advance understanding of what conservation actions are possible in diverse contexts (Sutherland et al. 2004) and contributes understanding the processes that serve to improve or weaken management of natural resources (Ostrom 2009). In particular, we respond to calls from institutional analysis theorists to further unpack the variables that are linked with successful and unsuccessful natural resource management outcomes (Sick 2008; Ostrom and Cox 2010; Blomquist and deLeon 2011; Ostrom 2011b; Clement 2012; Vogt et al. 2015). Second, this research draws attention to dryland riparian SES, which although recognized as hydrologically and ecologically unique, biologically sensitive providers of highly valued ecological goods and services, have not received adequate attention in the natural resource management and conservation literatures. Third, our findings shift attention away from broad, one-size-fits-all policy solutions to transboundary conservation further confirming Ostrom’s (2009) argument that “simple blueprint policies do not work” (421), even within a common resource system. Instead we attend to the particularities of multi-scale interrelations and interdependencies between actors, institutions, and ecologies in riparian SES and the surprising outcomes that these complex, historically and geographically situated
interactions may invoke.

The paper proceeds as follows. In the next section, we present the theoretical framework, Ostrom’s SES framework for institutional analysis. The third section presents the comparative institutional analysis of the two riparian conservation attempts, including our methodology for data collection and analysis. In this section, we detail common characteristics of the transboundary San Pedro River and aquifer system and introduce the two specific riparian conservation case studies, the SPRNCA and the Mavavi. The fourth section presents the results of our analysis, specifically, our characterization of the four key factors that emerged from the comparative analysis and the corresponding significant socio-political and ecological variables derived from the SES framework. The fifth section concludes the paper.

Theoretical Framework

The SES Framework: Linking Institutional Analysis and Socio-Environmental Variables

In complex riparian SES, there is a bi-directional link between social and economic processes and biophysical change in riparian hydro-ecology. Changes in these processes are mutually-constitutive, meaning that the social sphere and the physical sphere impact one another, making and re-making the other in an iterative fashion over time. Socio-economic processes and practices transform biophysical processes within the riparian corridor. These changes in the physical system in turn feedback to influence socio-economic processes and practices that shape the ‘rules in play’ (Ostrom 1990). The rules in play are more expansive than just written, formal rules, instead including multi-scalar structures of authority and power, livelihood practices, and customs, norms, and behaviors of resource extraction, consumption, and disposal. Said another way, the rules in play impact the appropriation and distribution of benefits derived from the
resource area to different individuals and groups.

Institutional analysis presents an integrated framework within which to examine the connectivities and interrelations between the bio-physical properties of the resource and the rules in play, comprising the management and ownership characteristics of the resource (i.e. private, public, or common-pool) and relevant social attributes, including relations of trust and reciprocity (McGinnis and Ostrom 2014). Shifting institutional arrangements produce material transformations in biophysical landscapes, which in turn transform resource use behaviors and livelihoods. We argue that institutional analysis provides a useful theoretical and analytical framework to assess the process of establishing and implementing natural resource conservation in transboundary environments. In our case of riparian conservation in the transboundary San Pedro River watershed, the SES framework helps to reveal the interdependent relations, feedbacks, and tensions present between the human system variables (i.e. governance system; actors) and biophysical system variables (i.e. resource system; resource units) that influenced the specific outcomes of the two conservation cases.

The decisions of actors to extract and consume resources, such as water, both depend on and exert influence over the institutional possibilities and constraints. Thus, conceptual frameworks of institutional analysis must consider the political, social, and ecological contexts in which natural resource practices take place, including current and historical configurations of ownership and access, and recognized rights to and established norms of resource use. For example, to achieve sustainable watershed management, Davenport and Seekamp (2013) argue that the successful creation, implementation, and long-term functioning of policy requires serious attention to human conditions, biophysical resource characteristics, and the interactions of the social and ecological system. Recent institutional scholarship focused on natural resource-based
conflicts suggests identifying and characterizing catalyst events that serve to initiate collaboration, galvanize collective action, and build capacity for collective response (Davenport and Seekamp 2013; Prokopy et al. 2014) and recognizing the role of leaders who can act as catalysts to create social capital or bridge to higher levels of institutions with increased access to power (López-Gunn 2012). Discursive problem framing has also been found to be a key variable, because how and by whom problems are framed impacts perceptions of causation, assignations of blame, and narrows the range of possible solutions (Ebbin 2014). Thus, understanding the intricate and complex relations between stakeholders is critical for what Ebbin refers to as ‘the problem with problem definition’. At the center of the problem of problem framing are conflicting ideologies that structure understanding of human-environment relations, including appropriate forms and levels of resource allocation, resource use behaviors, and conservation priorities. In cases of transboundary protected area governance, Petursson et al. (2011) argue that attention must be paid to local stakeholders’ rights and responsibilities, to the existing relationships between resource users and local authorities and resource managers, to resource access dynamics, and to rules of appropriation.

The SES framework organizes four interrelated first tier variables, each of which can be deconstructed into more specific and empirically grounded second-tier and third-tier variables: resource system (RS), resource units (RU), governance system (GS), and actors (A) (Ostrom 2009; McGinnis and Ostrom 2014). These variables shape and are shaped by the social, economic, and political setting (S) and the related ecosystem (ECO) (Figure 2). The first tier variables share relations with each other, where resource units are understood as part of the resource system and the governance system defines and sets the rules for the actors. At the center of the SES framework is the focal action situation, first theorized in the IAD framework. Focal
action situations are dynamic processes that transform interactions (I) between actors into outcomes (O).

The four first-tier variables are related to the action situation as follows: the resource system and the governance system set the conditions that structure the action situation, while actors participate in the action situation, and resource units provide the inputs. In transforming interactions into outcomes, dynamic action process also serves to transform the resource unit inputs and relations between actors, thus the action situation is related back to the four classes of variables via feedback loops (Ostrom and Cox 2010; McGinnis and Ostrom 2014). Each generalized first-tier component contains second-tier (Table 2) and third-tier variables that develop the specificity of the system. In certain systems and situations not every second-tier or third-tier variable may be present or particularly important, thus the framework allows for adaptability in how it is utilized in different contexts and geographic locations. The SES framework explicitly attends to the relationships between rules, incentives, and actor behaviors, and recognizes the implications of these relationships for catalyzing collective action and decision-making, conflict, and/or cooperation. The central placement of the dynamic and transformative action situation at the heart of the SES framework illustrates that varying institutional configurations produce material differences in resource units and resource systems and feedback to affect actor groups and governance system dynamics.

In the next section, we turn our attention to the comparative institutional analysis of two attempts to establish riparian conservation areas on the transboundary San Pedro River. We present the methodology, including the data collected and analyzed, introduce the study area of the transboundary San Pedro River watershed, and discuss the two specific cases, the SPRNCA and the Mavavi in greater detail.
Methodology and Study Area

Methodology

This research presents a comparative analysis to examine the establishment of the San Pedro Riparian National Conservation Area (SPRNCA), in southern Arizona on the US-portion of the watershed in 1988 and the failed attempt to establish the Mavavi protected natural area in northern Sonora, on the Mexican portion of the watershed during the period 1997-2003. This research is a retrospective assessment of the two cases based on the analysis of historical data and key informant interviews. To collect and analyze our data, we employed the SES framework. We characterized the San Pedro River watershed by the first-tier components and through an iterative process identified the key second-tier variables for each component and the feedbacks to the components based on the interactions and outcomes within the transformative focal action situations. This approach enabled us to identify and organize the relevant characteristics of the system and later to analyze these characteristics and synthesize the variables to determine the four key processes we present in Section 4 of the article.

The data presented in this article was collected by the authors through interviews with key actors who participated in the Mavavi process, compilation of documents from archives in Tucson and Sierra Vista, Arizona and Cananea and Hermosillo, Mexico, newspaper articles, and requests for reports housed in participating government agencies and organizations. The data analysis consisted of textual analysis of the archival documents, newspaper articles, transcripts of meetings and submitted public comments, and government agency documents and reports. The interview transcripts were coded based on the second-tier variables (Table 2) presented by Ostrom (2009). We utilized a mixture of deductive and inductive reasoning. While the SES
framework drove our hypothesis of key variables and system dynamics, the analysis of the
textual data and the interview transcripts revealed certain surprising variables and actions that we
had not hypothesized. The analysis of empirical data serves to: identify the “rules in play”
(including formal laws, and regulations and informal norms and customs that guide resource use
behaviors); define and explain the roles that diverse actor groups play in conservation
deliberations; contextualize the complex ecological and hydrological landscape within which
conservation deliberations are situated; and map the institutional linkages that draw resource
ecologies, resource users, and governance systems into relation, serving to either facilitate or
impede dryland riparian forest conservation in a transboundary context.

The Transboundary San Pedro River and Shared Aquifer

In this section, we characterize the biophysical and hydrological aspects of the
transboundary San Pedro River, focusing on the resource system (RS) and resource unit (RU)
components. We identify the significant second-tier variables of the RS, the RU, and the larger
related ecosystem (ECO) (Table 2). The transboundary San Pedro River originates in northern
Sonora, Mexico in the mountains near the copper mining center of Cananea and flows north into
the United States through southern Arizona, where it meets the Gila River, which eventually
flows into the Colorado River. Principal recharge of the alluvial aquifer, which holds much of
the available groundwater in the upper basin, depends on streambed infiltration and mountain-
front recharge (Pool and Dickinson 2006). The 1,875 square mile basin receives between 300 to
750 millimeters of precipitation per year, with 65% of precipitation occurring between July and
September during the monsoon season.

The San Pedro River riparian forest is characterized by high biodiversity, providing critical
habitat for a number of recognized endangered species, including more than 80 species of mammals, native species of fish, more than 40 species of amphibians and reptiles, 100 species of breeding birds and 250 species of migrating birds (Stromberg and Tellman 2009). The combination of highly variable precipitation patterns, heavily irrigated agriculture and rapid population growth has resulted in steadily increasing groundwater withdrawals that currently exceed the natural rate of recharge. This unsustainable use of water resources has led to severe reductions in flow. The river has lost over half of its historical perennial surface water flow, a condition aggravated by high well densities in close proximity to the river (Browning-Aiken et al. 2007).

In the next section, we identify the SES variables significant for comparing the cases of the SPRNCA and the Mavavi: governance system (GS), actors (A), interactions (I), and outcomes (O) (Table 2). These variables allow us to systematically compare the cases and determine answers to a number of key questions: Who were the actors in each case and how did they self-organize in favor of or in opposition to the conservation plan? What were the perceived impacts of the establishment of a national conservation area on economic development and production activities, including ranching, mining, urbanization, and agriculture? What are the ‘rules in use’ across the transboundary watershed and how do they differ?

**Comparative Institutional Analysis of Two Riparian Conservation Attempts on a Common River**

**Case 1: Establishment of the San Pedro Riparian National Conservation Area (SPRNCA), Arizona, USA**

In the mid-1980s, a decade following the passage of the 1973 Endangered Species Act
and the 1976 Federal Lands Protection and Management Act, a transboundary project to conserve the river began to take shape. As a response to dramatically decreasing surface water and ecological degradation in the riparian zone, in the mid-1980s pressure began to build to conserve the river and the riparian ecosystem. In 1986, Senator Dennis DeConcini of Arizona submitted a statement to a Senate subcommittee hearing depicting the unique ecosystem of the San Pedro River riparian zone, “it encompasses an entire fragile ecosystem which can be easily tipped off balance by the slightest misuse” (DeConcini, 1986, p. 5). DeConcini’s description of the ecosystem using the language of balance and fragility highlights one prominent discourse, that of maintaining social-ecological system resilience, that weaves throughout both the SPRNCA and Mavavi conservation processes.

In April 1986, the Bureau of Land Management (BLM) acquired 43,371 acres of land along the Upper San Pedro River through a land exchange (DOI 1988). During the 1980s, the BLM had an aggressive land tenure adjustment program, using land exchanges with private owners to amass a portfolio of high value lands across the Western United States. The San Pedro riparian area, once part of the historic San Juan de las Boquillas y Nogales and San Rafael del Valle Spanish land grants dating back to 1827, had been under the private ownership of the Tenneco Oil company since 1971 when it gained the title to the land through the acquisition of the previous owner, the Kern County Land and Cattle Company (Cowgill 1986, 1989). However, by the 1980s after a series of unsuccessful attempts to develop the land, Tenneco was looking for a way to dispose of the large landholding. White Tank Associates/H.B. Bell Investments, Inc. a private Phoenix-based land developer purchased the lands from Tenneco for $26.5 million and then entered into the exchange with the BLM, trading the San Pedro River property for 40,000 acres of BLM land near Phoenix (Cowgill 1989). Additional smaller land acquisitions from
private owners to the BLM expanded the BLM’s San Pedro holdings to include three additional miles of riparian habitat between Hereford, Arizona and the US-Mexico international border, bringing the total area to 56,000 acres. Upon taking control of the land in March 1986, the BLM immediately closed the land from access to the public, imposed a 15-year moratorium on cattle-grazing, canceling the grazing leases that Tenneco had managed with local ranchers, and retired 40 agricultural wells (12,000 acre-feet of agricultural water rights) (Vorhes 1988; BLM 1988a). While waiting for the US Congress to determine the fate of the San Pedro riparian lands, the BLM continued its policy of restricting access to the property. Hundreds of public comments submitted to the BLM and the transcripts from two heated community meetings depict a situation rife with conflict within the local community, especially with ranchers, hunters, bird watchers, and Fort Huachuca, the military establishment that borders the property (BLM 1988b). In the Spring of 1987, Fort Huachuca requested that soldiers be allowed to enter the BLM’s property for a training exercise with tanks, which the BLM quickly denied, further drawing the ire of the Department of Defense (Vorhes 1988).

In 1988, under mounting pressure from environmental agencies and conservation groups, the US Congress passed the Arizona-Idaho Conservation Act (Public Law 100 696), which included the designation of a 40-mile conservation area on the BLM’s property, to be known as the San Pedro Riparian National Conservation Area (SPRNCA), the first federally recognized riparian conservation area in the US. The stated mission of the establishment of the SPRNCA is “to protect the riparian area and the aquatic, wildlife, archaeological, paleontological, scientific, cultural, educational, and recreational resources of the San Pedro River”(BLM 1988a). Following the passage of the Arizona-Idaho Conservation Act, the BLM was tasked with re-opening the property to the public, but in a way that would be in line with the SPRNCA’s stated
mission. In June 1988, the BLM filed a draft Environmental Impact Statement (EIS) with the Environmental Protection Agency (EPA) (BLM 1988a). The document listed four alternatives for the management plan for the land. All four alternatives continued the moratorium on grazing and agricultural activities, thus excluding livelihood activities from the protected riparian zone for the long-term (BLM 1988a). The grazing moratorium and subsequent hunting ban fueled a controversy evident in the public comments received by the BLM for their planning document and environmental impact statement (BLM 1988b). Much of the argument against the grazing moratorium drew on the Multiple Use concept, which founds the management philosophy of the BLM and other US governmental agencies, including the Forest Service, enabling these agencies to permit productive activities on federal and state lands, including grazing, timber harvest, and hunting. In response to the debate on Multiple Use and the future of riparian management within the SPRNCA, the BLM argued that the Federal Land Policy and Management Act supports “that not all uses have to be allowed to occur on every parcel of public lands,” thus the BLM could restrict productive activities in the SPRNCA to fulfill its mission to protect the unique qualities of the riparian zone (BLM 1988a). Furthermore, because the BLM had acquired the San Pedro riparian lands through an exchange with private landowners and the establishment of the conservation area was approved in Congress before any local public meetings, the backlash against the BLM during the public comment periods in 1988, had little impact on the future management directions for the land.

However, the SPRNCA only applied to the US-portion of the river, importantly, the downstream section; which allowed activities (including ranching, mining, and irrigated agriculture), deemed exploitative to conservationists, to continue in the upstream, on the Mexican portion of the river. In 1997, an Arizona Department of Water Resources report, titled
“City of Sierra Vista, Arizona… Flowing in the Right Direction” reported that 5,000 acre feet of water was being diverted from the river in Sonora to irrigate farm land and pasture, creating a local panic that focused blame for reductions in flow into the SPRNCA on agricultural producers in Mexico (ADWR 1997). In September of 1998, an Arizona Daily Star newspaper article titled, “Panel Predicts a Dry San Pedro” (Bodfield 1998) called for the US to begin buying irrigation rights in Sonora and retiring them to reduce agricultural irrigation on the upstream Mexican-portion of the river. These and other ‘aggressive strategies’ (Star, 12 April 2000) to reduce water consumption were met with resistance in Mexico, where agrarian communities viewed the US as jostling for territorial control and as an infringement on Mexican sovereignty.

Case 2: Failure to Establish the Mavavi Riparian Natural Protected Area, Sonora, MX

Since the 1970s, groundwater demands in the Mexican region of the San Pedro river have increased significantly due to rising production at the large copper mine located in Cananea, which contains an estimated 2-3% of the world’s known copper supply (and represents 30-40% of Mexico’s copper production), rapid urban growth, and shifting agricultural and ranching practices. In the 1980s, under the administration of President Miguel de la Madrid, institutions for environmental protection began to proliferate in Mexico, beginning with the establishment of the National Commission for Natural Protected Areas (originally SINAP, but in 2000 reformed to CONANP as it is known today, Spanish initials). In 1988, the Mexican legislature passed a new natural conservation and sustainable development law, The General Law for Ecological Equilibrium and Environmental Protection” (LGEEPA, Spanish initials). The 1990s saw a continuation of the political climate in favor of environmental conservation action, with the political promotion and financial support of new Natural Protected Areas (ANPs, Spanish
initials). In 1996, LGEEPA was reformed to strengthen SINAP creating the possibility of joint management between agencies to more effectively manage conservation areas through multi-organization coordination. Furthermore, the 1996 reforms to LGEEPA ruled that the proposal of an ANP must come from community actors and/or organizations, reflecting a shift, at least on paper, to a bottom-up emphasis in conservation away from complaints that conservation was being imposed on communities from above. Along with the ANP reform came the mandate that every ANP proposal be accompanied by a 30-day public comment period, reflecting the establishment of the National Program for Solidarity (PRONASOL, Spanish initials) meant to ensure that the government attends to public scrutiny and social criticism of public programs.

Following the growing emphasis at a national level on conservation in the 1980s and 1990s, in 1997, the secretariat of the Commission for Environmental Cooperation (CEC), established under the North American Agreement on Environmental Cooperation (NAAEC), the environmental arm of the North American Free Trade Agreement (NAFTA), launched the binational ‘Upper San Pedro Initiative.’ Two years later in 1999, the “Divided Waters, Common Ground” conference held in the Sonoran San Pedro set the wheels in motion to spatially define the extent of the proposed Mavavi Natural Protected Area for Flora and Fauna (ANPFF, Spanish initials), which would significantly extend the existing 184,000 hectare Ajos-Bavispe protected area to 780,114 hectares to include much of the Sonoran-portion of the San Pedro watershed, including the riparian zone, but also crucially copper and other mineral deposits slated for future extraction (SALSA 2000; SEMARNAP 2001). In 1999, Bruce Babbitt, then Secretary of the U.S. Department of the Interior, gave the keynote address for the 1999 Divided Waters, Common Ground Conference (SALSA 2000).

“This conference is a milestone event in the preservation of the San Pedro River. One of the last intact riparian ecosystems in the Southwest, the San Pedro River
remains at risk due to our failure to meet our obligations to the land, its resources, and to the future. *Looking across the border, the emerging partnership between Arizona and Sonora is a powerful success story.* We have come a long way in overcoming the cross-border communication barriers that existed twenty-five years ago when I was governor of Arizona. Recently, at [Secretary Julia Carabias’] suggestion, we searched for natural areas along the border and zeroed in on the San Pedro River as a landscape where the future is still developing, where we could develop a partnership across the border, and where we could learn from each other. We agreed to do everything possible to facilitate communication between Arizona and Sonora to preserve the river. *This is not about compromising sovereignty; rather, about creating a new model, a common landscape where a new binational culture would be created out of the best of both cultures.*” (SALSA 2000: 12-13, emphasis added by author)

The *Divided Waters, Common Ground* conference was an early success in what would ultimately be a failed attempt to establish a riparian conservation reserve on the Mexican-portion of the San Pedro River to mirror the SPRNCA in Arizona.

Following the conference in July 2000, the first proposal for the Mavavi Conservation Reserve was presented to a binational group of academics, scientists, and stakeholders (López et al. 2008). The plan proposed a non-contiguous reserve covering an area of 780,114 hectares, an area containing 106 mining concessions (representing 90% of Mexico’s copper production) and 59 additional groundwater wells (a number now greatly increased (House-Peters 2016, in review)) serving irrigated agriculture, ranching, and rural domestic water supply. The boundaries of the original proposed Mavavi area (SEMARNAP 2001) also included a site that Grupo Frisco, a mining development firm owned by Mexico’s richest man, Carlos Slim, was planning a $760 million investment. Hardly 5 months after the original proposal, in November 2000, the second proposal more than halved the proposed reserve area to 370,341 hectares. The third and final proposal in September 2001, just before the final failure of the plan, presented a slightly further reduced area of 367,541 hectares, but which importantly still included significant copper reserves (CONANP 2002).
For Grupo México’s Buenavista del Cobre mine located in Cananea, the establishment of the Mavavi Reserve was highly problematic. Interview informants shared that the establishment of the Mavavi Reserve, particularly the geographic area covered in the first and second proposals, threatened the mine’s access to new supplies of mountain-top copper and proposed prohibitions on well placement, depth, and pumping amount, thus creating obstacles to the future planned expansion of the mine. As a response to the threat of losing access to deep groundwater wells located in the riparian corridor, officials from the mine worked to successfully counter-organize local ranchers against the Mavavi Reserve on the grounds that ranchers and farmers would lose access to the land and water resources they relied on for their livelihoods (Julia Carabias Lillo, personal communication).

Resistance to the Mavavi plan played off historical and recurring contemporary fears that the US was leveraging their role in the binational Mavavi deliberations to encroach on Mexican sovereignty and to take control of the headwaters of the river in Sonora and to increase flows into the US to support urban development. Funding to support the Mavavi was split between the US and Mexico, including financial commitments from the US Secretary of the Interior, Bruce Babbit, the National Fish and Wildlife Service, the World Wildlife Fund, The Nature Conservancy, and the David and Lucile Packard Foundation (SALSA 2000). Based on interviews with local community members, U.S. financing raised alarms that the U.S. would expect something in exchange for its investment.

Looking to the experience of conservation in the US riparian corridor, producers saw the prohibition of working landscapes and the exclusion of production from the highly productive 3-mile zone surrounding the river and the forested riparian corridor, key sites for agriculture and grazing. Ironically, the ultimate rejection of the Mavavi conservation area due in large part to the
mining interests’ co-optation of small local producers, has resulted today in non-regulated, explosive growth of extractive industry in the headwaters of the San Pedro River. This has led to rapid aquifer depletion to support copper extraction and concentration processes and severe water shortages and loss of livelihoods for many of these same agricultural producers, who had feared loss of control over their local natural resources due to regulations that would be imposed under the Mavavi plan.

**Four Key Factors of Riparian Conservation Deliberations**

We characterize the key processes of the two cases of riparian conservation attempts, identifying and grouping relevant second-level variables from the SES framework (Table 2) into four explanatory factors. This analysis contributes to advancing understanding of processes of conservation establishment in binational watersheds.

**Legitimacy, Uncertainty, and Authority of Competing Sources of Ecological Knowledge**

Knowledge sharing and information flows (I2) are understood to significantly strengthen transboundary adaptive management (Varady et al. 2013). Results of a case study of climate change adaptation planning in the US-Mexico border region show that beyond binational collaboration and the involvement of multiple institutions from both countries, it is necessary that the information currently used by actors and organizations be well-understood. Further, the development of new information products should be designed based on the criteria of accessibility, ability to be easily shared, and intelligible to a wide audience.

In riparian zones, the strong coupling between surface water and obscure groundwater dynamics (R7) tends to elude the full comprehension of scientists, experts, practitioners, and
water users (U7). The partial and varied understandings of the dynamics and equilibrium properties between surface and groundwater (R6, RU2) pose significant challenges to developing trust, legitimacy, and cooperation and can spark divisive conflict among actors (U5). In the case of the Mavavi reserve, the difficult to quantify and model properties of the San Pedro aquifer and the relation to streamflow volumes created competing understandings among participants of the Mavavi planning process (U7, I3). For example, baseflow, although a critical component of the water balance, is notoriously difficult to measure and sensitive to a number of factors, including season, changing evapotranspiration demands of vegetation, and near-stream pumping (RU1).

In 1999, José Manuel Barcelo, President of Ejido Zapata, argued that “while the ejido’s wells are dry, the mine has enough water for its activities.” However, Isaac López, Director of Operations of the mine, immediately countered “preliminary results [of a hydro-geologic study] indicate that system recharge is greater than previously believed, thereby indicating that the aquifer is underexploited.” Though López admits “accurate assessments of evapotranspiration, flow toward the San Pedro River, and the underground flow through the divide toward the United States have not been determined” (Quotes are taken from meeting transcripts published in SALSA 2000). This statement exemplifies the partiality of knowledge regarding complex riparian hydrology that continues to be a problem in the basin, eluding both scientists and stakeholders. In 1999, the mine also began implementing an “ambitious project in comprehensive hydrological control” that included constructing channels to divert captured rainwater to specific areas of the basin (SALSA 2000). In interviews conducted in the Mexican portion of the watershed, informants mentioned that they believed that one strategy of the mine to keep up the appearance of steady groundwater levels was to re-engineer water flows to the small lakes in the northern reaches of the basin, where dropping water levels were visible and
often created the greatest backlash from watershed residents toward the mine’s exploitation of the aquifer (U7, O3).

**Multi-scalar Institutional Networks: Misalignment and Dissonance**

In transboundary watersheds in the US-Mexico border region, legal and regulatory asymmetries persist (Megdal and Scott 2011; Milman and Scott 2010), leading to institutional misalignment and dissonance that complicates goals to achieve well-aligned and integrated water resource management (Ruiz et al. 2011). Both the SPRNCA and Mavavi entail large numbers of actors and organizations at multiple scales from the local to the national to the international, in the case of the Mavavi (Figures 3 and 4) (U1, I1). However, an important difference between the experience of the SPRNCA and the fractured Mavavi deliberations was the BLM’s ability to acquire the majority of the conservation property through one large private land exchange (GS4).

BLM’s control over the land and the subsequent establishment of the conservation area by the US Congress streamlined the process, in effect making the deliberations that occurred after SPRNCA’s establishment more of a formality than an actual political process (I6, I8). Thus conflicts that raged over the moratorium on grazing and the hunting ban in the riparian area were carried out with low possibility of actually making a substantial impact to the management planning process (I1).

In the case of the Mavavi proposal, the deliberations had high stakes, as the LGEEPA law required that public participation and public support for the conservation proposal be a central part of the planning process. Because the land area that the Mavavi would have conserved was very large, much larger than the SPRNCA, control over the land was held by many different private owners, including powerful mining companies, and covered multiple land uses, including
agriculture, ranching, and extractive industry (RU3, RU4, GS4, U1, RS2, O3). Thus, a simple exchange between two parties was never an option on the table. Thus any misalignment in goals or understandings that arose between different actors could exacerbate the already difficult process, making success an extremely unlikely outcome (I8, GS6, U6).

The existence of diverging visions of conservation and interpretations of environmental problems is known to alter the decision-making context and can lead to conflict (Ruiz et al. 2011). In the Mavavi case, differing understandings of the riparian ecosystem among different actor groups impeded the process (I3, O2, U7). For example, ranchers viewed the riparian zone as stable, clean, and healthy, well-cared for by the community, who understood themselves to be the caretakers of the environment on which their livelihoods depended. In opposition to this view, non-governmental organizations and environmental agencies represented the riparian area as unique, fragile, degraded, out of balance, and in need of immediate, outside protection (RU 3, RU 4, U6).

Community Politics and Intergroup Alliance Formation

Previous research on the San Pedro River has examined the role of binational alliances in conservation of the riparian resources (Browning et al. 2004; Ruiz et al. 2011), but has neglected to focus on the role that unanticipated alliance formation plays in conservation outcomes. Binational sustainability efforts have been found to be most successful when they focus on social equity and foster collective action of binational actors, as active participation of diverse social actors is central successful conservation processes (Ruiz et al. 2011). Conversely, imposing conservation strategies inappropriate the local context is likely to end in failure. Ebin (2014) argues that the framing of natural resource and sustainability problems serves to bound the range
of possible management solutions. Within the problem-framing, discourses about who will benefit, who will lose, and who is at fault for the current state of environmental degradation can become extremely powerful. In the case of the Mavavi, discourses became rallying cries around which unexpected groups aligned forming surprising alliances in resistance to the conservation area proposal.

In 2000, during the second year of the Mavavi planning process, the mining industry joined in the fight against the establishment of the conservation area. The mining industry began to organize around a discourse of conservation, but not in supporting the modality being proposed by the natural resource agencies fighting for the implementation of the ANP (GS6, I4, I7, RU4, O3, U5). Instead, the discourse focused on local forms of conservation, in opposition to the ANP-model, which was presented as an externally imposed and overbearing state regulation and a loss of local autonomy over decision-making (GS6, U3). This argument was purposefully crafted to align well with similar fears over loss of control of resources and distrust of the federal government expressed in the local agrarian communities to garner support in opposition to the Mavavi plan (O2, I4, I7). Powerful ranching actors also sought to control the discourse, representing Mexico as a victim of international treaties meant to serve US interests and the Mavavi as just another ploy to undermine Mexico’s sovereignty over its natural resources and to increase water flows to the US to support urban development and growth (U3, U7, I1, GS8, RS3, RS7, RU2). Around these shared concerns, mining interests and local agrarian populations coalesced forming an unexpected alliance to challenge and ultimately defeat the Mavavi proposal (I7, GS6, U5, U6).

Level of Correspondence between Policy Discourse and Local Material Concerns
Within the boundaries of the SPRNCA agrarian activities were eliminated, explicitly creating a zone of exclusion for livestock grazing and agricultural production. The designation of the SPRNCA further fragmented an already internationally divided riparian space, establishing asymmetrical land management practices on either side of the border; as part of the river flowing through Arizona was designated a ‘livestock-free’ landscape, while open-range cattle grazing and livestock production continues in Sonora (U1, U2, U8, I1, I4, RS5). Kelly (2011) contends that conservation serves as a mechanism for the ‘legalized seizure’ of property in the form of protected areas. Powerful narratives that privilege the conservation of wildlife and natural resources through the exclusion of certain groups serve to legitimate the creation of these protected areas.

The conservation approach of the SPRNCA exemplifies a traditional species-by-species orientation to conservation that produces policies that prohibit working landscapes in favor of protecting an individual threatened or federally-listed endangered species. Within the SPRNCA boundary, the moratorium on grazing was legitimated as a necessary management strategy to preserve the habitat of a small number of federally-listed endangered species (O2, RS1, RS5, I1). At the other end of the spectrum is the landscape-scale ecosystem-based approach, which recognizes the central role that local actors play in conservation management and monitoring. In contrast to the SPRNCA’s species-by-species approach, which places responsibility for biodiversity monitoring and management in the hands of government agencies, such as the Bureau of Land Management (BLM), an ecosystem-based approach recognizes that in practice, it is the local people who act as the on-the-ground, everyday managers of the land. For example, Sheridan (2014) argues that ranchers are the people who “provide the eyes on the ground to monitor environmental conditions and human impacts, legal and illegal, that affect the ecological
health of county lands” (264).

The presence of large, transnational extractive industry in the watershed, in this case the mega mining company Grupo México, complicates the landscape-scale ecosystem approach to conservation. This approach to conservation assumes that local actors are able to exert control over the management of local natural resource systems (GS6, U1, U2, O1, RS5, RU4). When non-local actors motivated solely by extracting profit are present and in control of large portions of the natural resource base, such as the majority of groundwater concessions in the watershed, the underlying logic of conservation is challenged. Species-by-species inventory approaches to conservation are often more attractive to large-scale industry because they advocate market-based environmental restoration and remediation programs based on the commodification of individual species, thus allowing the trade of natural resources between sites. The popular, and heavily critiqued, ecosystem services and wetland credit trading approaches are good examples of this type of conservation (Robertson 2006, 2012). At the heart of this predicament is the role of value, where non-locally based, profit-motivated corporations may hold very different notions of value, than local actors (Robertson and Wainwright 2013). This is an important limitation of the research. The rapid infiltration of transnational mining corporations across Latin America makes it necessary that new conservation frameworks emerge that are able to incorporate the influence of powerful actors who lack a stake in the social-ecological health of a locality, bar the ability to continue to extract profit.

**Conclusion**

Conservation of dryland riparian resources requires attention to institutions that shape human-environment interactions, such as practices of resource extraction, consumption, and
disposal. Employing the SES framework for institutional analysis, we characterize two attempts to establish riparian conservation areas in a transboundary watershed, one that succeeded and one that failed. Following Ostrom’s SES framework, we integrate data across the social and ecological systems to identify key variables within the social, economic, and political setting (S), the biophysical ecosystem setting (ECO), the resource systems (RS) and resource units (RU), the governance system (GS), the actors (A), and the interactions (I) and outcomes (O) that form the focal action situations. Analyzing the key variables we identified, we are able to derive four processes of riparian conservation deliberations in a transboundary context: 1) Legitimacy, uncertainty, and authority of competing sources of ecological knowledge; 2) Misalignment and dissonance within multi-scalar institutional networks; 3) Community politics and intergroup alliance formation; and 4) Level of correspondence between policy discourse and local material concerns.

We find that performance within these processes helps to explain why some deliberations to establish conservation areas succeed, while others fail. Our analysis reveals unexpected institutional dynamics, we find particularly important the presence and persistence of misalignment and dissonances within multi-scalar networks of local citizens, government agencies, and non-governmental organizations. These actors tend to come to the table with different perspectives on conservation and uneven understandings of riparian system dynamics, especially the highly coupled and obscure interactions between groundwater and surface water. When active attempts to resolve these differences are absent we find misalignments lead to misunderstandings and ultimately to conflict, which inhibits collective action in favor of conservation outcomes. The lack of agreement over how collective action should proceed may create a vacuum, where unexpected alliances form, especially when common fears of losing
access to natural resources and distrust of state regulation shared across otherwise dissimilar actor groups are not alleviated. In the Mavavi case, these processes coincided to cement a strong anti-conservation movement – the alliance between mining interests and local ranchers – based on a shared “política de no conservación”, leading deliberations to stall and ultimately to fail.

In SES characterized by complex biophysical dynamics, such as dryland riparian SES, trust in sources of ecological knowledge and the willingness to openly share data, especially when there are conflicting opinions about the drivers of change is of paramount importance. In the San Pedro River riparian corridor, the coupled, yet invisible, system dynamics between groundwater and surface water impact water availability and riparian forest health. The invisibility of groundwater supplies, the long temporal lag between recharge and extraction and ecological impact, and the low predictability of system dynamics intersect to create a situation marred by confusion and competing sources of knowledge. Coupled with the absence of strong leadership by a coalition of interests, lack information sharing, and no official acknowledgement of possible externalities that different conservation scenarios are likely to produce, the chances for successful deliberations are extremely low. Finally, we find that deliberations are unlikely to succeed when discursive framings of conservation policy do not correspond with the material concerns of the local community. The exclusion of people from access to resource bases on which their livelihoods depend to protect specific ecological species is likely to be unpopular. Surveying local material concerns and understanding how local producers envision conservation and their role in carrying it out is extremely important and should be an early step in the deliberation process.
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Figure 1: Map of the transboundary upper San Pedro River watershed that straddles the border of Sonora, Mexico and Arizona, USA. The red squares delineate the approximate locations of the two proposed riparian conservation areas, the SPRNCA and the Mavavi. The white outline is the formal boundary of the SPRNCA established in 1988. The Mavavi national conservation area was never established. The dashed line box represents the riparian corridor of the proposed location of the Mavavi reserve. The actual reserve covered a much larger area including the surrounding valleys and mountains within the Mexican portion of the watershed. (Map by author).
Figure 2: The SES framework (Reproduced from McGinnis and Ostrom 2014) illustrating the relationships between the first-level components (ie. resource systems; resource units; governance systems; actors; and interactions → outcomes). Each first-level component contains second- and third-level variables (see Table 1). In focal action situations, inputs are transformed by the actions of multiple actors into outcomes. The social, economic, and political setting and the related ecosystems are understood as exogenous influences that can affect the SES components. The dashed line arrows represent feedbacks from the outcomes in the action situations back to the SES components, thus impacting the system variables.
Figure 3: Institutional map of the establishment of the San Pedro Riparian National Conservation Area (SPRNCA). (Figure design credit: Kate Curl)
**Figure 4:** Institutional map of the Mavavi conservation area deliberations (Figure by the author)
Table 1: Second-tier variables of the SES framework nested under the first-tier categories depicted in Figure 2. The variables become more specific in such successive tier and can be further elaborated at third-tier and even fourth-tier specificity for a SES (Reproduced from Ostrom 2009).

<table>
<thead>
<tr>
<th>Resource systems (RS)</th>
<th>Governance systems (GS)</th>
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<tbody>
<tr>
<td>RS1 Sector (e.g., water, forests, pasture, fish)</td>
<td>GS1 Government organizations</td>
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<td>RS2 Clarity of system boundaries</td>
<td>GS2 Nongovernment organizations</td>
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<td>RS3 Size of resource system*</td>
<td>GS3 Network structure</td>
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<td>RS4 Human-constructed facilities</td>
<td>GS4 Property-rights systems</td>
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<td>RS5 Productivity of system*</td>
<td>GS5 Operational rules</td>
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<td>RS6 Equilibrium properties</td>
<td>GS6 Collective-choice rules*</td>
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<td>RS7 Predictability of system dynamics*</td>
<td>GS7 Constitutional rules</td>
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<td>RS8 Storage characteristics</td>
<td>GS8 Monitoring and sanctioning processes</td>
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<td>RS9 Location</td>
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<th>Resource units (RU)</th>
<th>Users (U)</th>
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<td>RU1 Resource unit mobility*</td>
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<td>RU2 Growth or replacement rate</td>
<td>U2 Socioeconomic attributes of users</td>
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<td>RU3 Interaction among resource units</td>
<td>U3 History of use</td>
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<td>RU4 Economic value</td>
<td>U4 Location</td>
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<tr>
<td>RU5 Number of units</td>
<td>U5 Leadership/entrepreneurship*</td>
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<td>RU6 Distinctive markings</td>
<td>U6 Norms/social capital*</td>
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<td>RU7 Spatial and temporal distribution</td>
<td>U7 Knowledge of SES/mental models*</td>
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<td>U8 Importance of resource*</td>
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<td>U9 Technology used</td>
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<td>I2 Information sharing among users</td>
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<td>I3 Deliberation processes</td>
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*Subset of variables found to be associated with self-organization.
Table 2: Four key processes of riparian conservation deliberations in a transboundary context with associated first-tier components and significant second-tier variables based on data analysis following Ostrom’s (2009) SES framework.

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<th>Interactions (I)</th>
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- RU 7: Predictability of system dynamics
- RU 4 Economic value
- RU 5 Number of units
- U 5: Leadership
- U 6: Norms/ social capital
- U 7: Knowledge of SES

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- RU 4 Economic value
- RU 5 Number of units
- Interactions (I)
  - I 1: Harvesting levels of diverse users
  - I 2: Information sharing
  - I 3: Deliberation processes
  - I 4: Conflicts among users
  - I 7: Self-organizing activities

- Outcomes (O)
  - O 1: Social performance measures
  - O 2: Ecological performance measures
  - O 3: Externalities to other SES
APPENDIX D

Developing an Updated Multi-temporal Land Cover Classification to Assess Riparian Conservation and Inform Decision-Making in the Upper San Pedro Watershed: A Classification and Regression Tree (CART) Model Approach

Lily A. House-Peters
David Chang

For Submission to: International Journal of Remote Sensing

Abstract

The Upper San Pedro watershed, located in southeastern Arizona and northeastern Sonora, experiences multiple competing demand for limited water supplies, including urban consumption, demand from a large military base, industrial copper extraction, irrigated agriculture, livestock production, and the often overlooked water demand from natural vegetation via evapotranspiration. Land cover maps are critical tools for assessing, analyzing, and managing ecological change, and for catalyzing conversations and enhanced communication among stakeholders and decision-makers. However, accurate, up-to-date land-cover maps are often lacking. For example, although the Upper San Pedro watershed has undergone considerable changes in land cover over the last decade, the most recent widely used land cover map is based on satellite imagery from the year 1997. The goals of this research are twofold. First, we provide an updated land cover classification map for the binational Upper San Pedro River watershed utilizing the Classification and Regression Tree (CART) approach to derive a 10-class land cover classification (kappa accuracy = 0.7511) that matches the land cover categories of a previous time series. Second, we characterize and assess changes to the landscape over a 25-year period (1986-2010) at both a regional, watershed scale and a local-scale within the 40-mile San Pedro Riparian National Conservation Area (SPRNCA), established within the Arizona-side of the watershed in 1988. The 2010 classification allows us to conduct a spatially-explicit analysis of land cover changes at both the binational watershed scale and within the San Pedro Riparian Conservation Area (SPRNCA), established in 1988 to protect the unique, highly biodiverse riparian corridor along the Arizona portion of the river. The 2010 land cover map has important significance for local policy- and decision-makers who rely on data generated by hydrological and ecological models, which currently rely on the outdated 1997 land cover data.
Introduction

In the arid and semiarid southwestern region of the United States, unique dryland riparian areas and associated uplands play host to a number of diverse and critical ecosystem processes and services (Newman et al. 2006). Riparian corridors — “the area from the edge of the stream bank to the external visible line of the canopy where an abrupt change in vegetation height, types, and amount occurs” (Johansen and Phinn 2006) — are vital habitat for diverse flora and fauna species, assist in controlling non-point source pollution, help to maintain cool water temperatures through shading, and afford numerous cultural, recreational, and aesthetic values (Bagstad et al. 2005; Ashraf et al. 2010; Wang et al. 2010). Riparian vegetation structure also provides protection against flooding, by attenuating peak discharge (Forzieri et al. 2010). This is especially important in ecosystems that experience intense seasonal variation in precipitation, as the riparian corridor acts as a first line of defense to moderate damage from flooding.

Land cover classification and change detection through remote sensing present effective methods for identification and analysis of social and environmental change over time at multiple spatial scales. These data are useful to land and water managers and policy makers to inform decision-making, as inputs to scenario planning, modeling, and analysis, and to determine the effectiveness of conservation on the restoration of specific land cover classes, such as riparian cover, over time. However, for this data to be effective for these uses it must be up-to-date and represent current land cover conditions. In the San Pedro watershed, land cover data is utilized by numerous natural resource agencies, conservation groups, and local stakeholders, including the US Geological Survey (USGS), the Bureau of Land Management (BLM), the U.S. Forest Service, the Friends of the San Pedro, and The Nature Conservancy. Yet the widely used 10-class land cover dataset for the Upper San Pedro River watershed developed by William Kepner
and colleagues at the Environmental Protection Agency (EPA) was last updated in 1997 (Kepner et al. 2000). In the thirteen year gap between 1997 and 2010, southern Arizona has experienced changing land cover due to rapid population growth and urbanization (Brown et al. 2005, Lang and Nelson 2007, MacDonald 2010). Furthermore, the studies that have utilized these data for analyses have been limited by its 60-meter spatial resolution, while comparable land cover datasets, such as the National Land Cover Dataset (NLCD), are classified at a 30m spatial resolution.

The goals of this research are twofold. First, we provide an updated land cover classification map for the binational Upper San Pedro River watershed, located in the US-Mexico border region of southeastern Arizona and northeastern Sonora (Figure 1). Second, we characterize and assess changes to the landscape over a 25-year period (1986-2010) at both a regional, watershed scale and a local-scale within the 40-mile San Pedro Riparian National Conservation Area (SPRNCA), established within the Arizona-side of the watershed in 1988. In this article, we present findings from a land cover classification performed on 2010 NASA Landsat imagery. We follow the robust Classification and Regression Tree (CART) method utilized for a recent high-accuracy land cover classification in the neighboring Santa Cruz watershed (Villarreal et al. 2011) to generate a 30-meter resolution land cover dataset for the Upper San Pedro watershed. The same 10-class land cover scheme used to develop the 1973, 1986, 1992, and 1997 time series (Kepner et al. 2000) was used in our new classification, making it possible to compare land cover across the series of classifications. The land cover classes include: forest, oak woodland, mesquite woodland, grassland, desertscrub, riparian, agriculture, urban, water, and barren (Figure 3) (see Kepner et al. (2000) for detailed land cover class descriptions).
Informing Riparian Conservation Policy Through Land Cover Change Assessment

Conservation of Binational Natural Resources

Worldwide, the effective and equitable management of transboundary watersheds and ecosystems, hydraulically or ecologically connected systems that traverse national boundaries, present significant challenges to natural resource governance (Megdal et al. 2012; Lopez-Hoffman et al. 2009). Implementing conservation of sensitive transboundary resources, such as biodiversity hotspots, surface and sub-surface water flows, and migratory land and air routes for endangered species, represent highly contested processes that often end in inequitable or unsustainable outcomes (UN 2009). In transboundary riparian corridors, such as the San Pedro River, ecological functions and processes flow across national political borders and boundaries, yet management regimes are bounded and asymmetric, producing a tapestry of interwoven, overlapping, and at times contradictory, rules, rights, and resource extraction and conservation practices. The existence of multiple agencies and organizations with distinct management priorities, ideologies, and political-economic settings challenges the establishment of integrative natural resource management. In the US-Mexico border region, transboundary collaboration for natural resource management is complicated by unilateral decision-making, institutional asymmetries, uneven topographies of power relations, distinct historical contexts and systems of property relations, diverse natural resource management ideologies, multiple, competing demands for resource use, distrust between actors, and uneven access to information about the social and biophysical characteristics of the natural resource system (Browning-Aiken et al. 2004; Wilder et al. 2010; Megdal and Scott 2011; Varady et al. 2013).

Because the decisions of actors to use and extract resources, such as water, both depend
on and influence institutional possibilities and constraints, policy makers must consider the political, social, and ecological contexts in which resources are extracted, utilized, and traded, including current and historical configurations of ownership and access rights, market mechanisms, and norms of resource use. To achieve sustainable watershed management, serious attention to human conditions, characteristics, and interactions is necessary for successful creation, implementation, and long-term functioning of policy (Davenport and Seekamp 2013). Identifying and characterizing catalyst events that initiate collaboration and galvanize collective action behavior leads to increased understanding of the mechanisms that encourage and promote collective action (Prokopy et al. 2014). In border communities, it is also necessary to account for are the rights, returns, relationships, and responsibilities among diverse stakeholder positions (Petursson et al. 2011). Understanding the intricate and complex relations between stakeholders is critical for what Ebbin (2014) refers to as the problem with problem definition. The author argues that in the context of natural resource-based conflicts, discursive problem framing is a key variable because how and by whom problems are framed impacts perceptions of causation, assigning of blame, and narrows the range of possible solutions. At the center of the problem of problem framing are conflicting ideologies that structure understanding of human-environment relations, including appropriate forms and levels of resource allocation, resource use behaviors, and conservation priorities.

The establishment of conservation areas and the implementation of conservation policy also transform how nature is understood. Differing and competing conservation ideologies create and may exacerbate conflicts between actors as local management and governance of the resource is affected. In relation to the transboundary San Pedro River watershed, previous research argues that any renewed binational sustainability effort focus on social equity and the
development of institutions that strengthen the collective action of binational actors and the 
integrated management of water resources, rather than imposing conservation strategies 
inappropriate to the local context (Ruiz et al. 2011). Ruiz et al. (2011) argue that central to 
achieving effective collective action is the active participation of diverse social actors. 
Furthermore, the decision-making context is altered by the existence of diverging visions and 
interpretations held by the actors and users on both sides of the border with respect to natural 
resource (land and water) rights.

In 1988, in an attempt to mitigate the environmental degradation occurring to the San 
Pedro River riparian corridor due to groundwater exploitation and urban development, the US 
Congress federally designated the San Pedro Riparian National Conservation Area (SPRNCA), a 
40-mile riparian zone conservation area (Steiner et al. 2000, Brookshire et al. 2010) (Figure 2). 
The purpose of the designation was to protect and enhance 56,000 acres of key desert riparian 
ecosystem, which is home to 84 mammal species, 14 fish species, 41 reptile and amphibian 
species and 100 bird species. The San Pedro River is also a critical flyway for North-South 
migration of birds; the SPRNCA provides habitat to over 250 migratory bird species, making it 
one of the top ten birding destinations in the world. Furthermore, the Upper San Pedro 
watershed contains critical habitat for seven threatened and endangered species, five of which 
rely on wetlands (Steinitz et al. 2003). However, a number of factors, both negative and positive 
have impacted the success of the SPRNCA, including steady population growth in the city of 
Sierra Vista, intensive groundwater withdrawal, decreasing precipitation, and the removal of 
grazing and most of the irrigated agriculture from the riparian area. The success of the SPRNCA 
remains contentious. For example, the USGS reported that between 1913 and 2002 (14 years
after the SPRNCA designation), surface water levels at the Charleston, Arizona gauge dropped a precipitous 90% in July and 80% in the months of August and September.

In the riparian corridor, biodiversity is critically dependent on hydrologic processes, specifically surface flow, shallow groundwater, and water quality, which are influenced in complex ways by both direct human intervention and broader climatic and landscape-scale processes. For example, aquifer depletion, due to excessive groundwater pumping to sustain agriculture and urban areas, reduces the amount and timing of water available to ecological communities in the riparian corridor. Fernandes et al. (2011) detail the impacts of adjacent land use change on riparian systems. The authors argue that the surface water extraction, groundwater pumping, grazing, nutrient inputs, and replacement of riparian forest with crops often concomitant with agricultural production, can result in a loss of riparian habitat complexity, increased stand mortality and decreased growth rates, and impacts on the ability of species, such as cottonwoods that depend on seasonal flooding, to successfully reproduce. The effect of urban development is an increase in runoff and sediment, the replacement of riparian habitat with roads and infrastructure, habitat fragmentation, increased levels of point and non-point pollution, and the introduction of non-native plant species. Importantly, the distributions of streamside plants, which comprise the structure vital for providing many ecosystem services, are dependent on numerous factors, including depth to the water table, rooting characteristics, and the riparian substrate geology, all of which are sensitive to the processes of land use change, including proximal agricultural and urban development (Amlin and Rood 2002).

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

Scenario Planning and Analysis for Policy and Decision Making

In natural resource management situations prone to conflict and with high uncertainty about future conditions, scenario planning and analysis is a powerful method for catalyzing conversations and enhancing communication among diverse stakeholders in a transboundary context, including land and water managers, urban planners, and conservationists (Scott et al. 2012). Scenarios represent a range a possible futures based on plausible forecasts of climate change, land-use change and population growth, which can be utilized to investigate how future water demand will change as a result of changes in climate and land-use patterns. The benefits of participatory scenario planning are well documented, including improved understanding of future uncertainties, integration of local knowledge, co-creation of a diverse set of robust adaptation options, and development of trust among managers and communities (NCA 2013; Scott et al. 2012). The result of these benefits is increased acceptance of the model outputs among stakeholders and improved likelihood that the model will be adopted by land and water managers and integrated in decision-making.
Yet, scenario planning and analysis requires tools that are user-friendly, up-to-date, and appropriately scaled (Steinitz et al. 2005; Kepner et al. 2004), such as high resolution, high accuracy, current land cover and land use data. Although previous research has explored a range of alternative future scenarios for impacts to groundwater in the Upper San Pedro River basin (Steinitz et al. 2003), these scenarios did not sufficiently consider the individual influences and impacts of water and land management activities occurring in the upstream portion of the San Pedro River watershed in Sonora, Mexico, nor were the scenarios spatially-explicit.

The 1,875 square mile binational Upper San Pedro River watershed faces the increasingly common challenge of determining how to balance competing demands for limited water supplies. For example, competing demands in the watershed include urban consumption in the cities of Sierra Vista, Arizona and Cananea, Sonora, the military installment at Fort Huachuca, increasing copper production at the massive Buenavista del Cobre copper mine in Cananea, irrigated agriculture, livestock production, and the often overlooked water demand from natural vegetation via evapotranspiration. To further complicate this scenario, there exist multiple, diverse agencies, organizations, and actors, and overlapping legal and territorial systems of property rights. Furthermore, the combination of highly variable precipitation patterns, heavily irrigated agriculture, rapid population growth, and the junior status of San Pedro River permit holders to Colorado River water from the Central Arizona Project has resulted in steadily increasing groundwater withdrawals that currently exceed the natural rate of recharge (Browning-Aiken et al. 2004; Kepner et al. 2004). Within the United States portion of the basin groundwater pumping has caused the San Pedro River to lose over half of its historical perennial surface water flow, a condition aggravated by high well densities in close proximity to the river (Browning-Aiken et al. 2007).
Methodology

Satellite remote sensing is an important tool for classifying land cover, assessing change over time, and monitoring conservation effectiveness, such as spatially-explicit characterizations of increasing or decreasing riparian vegetation. Moderate- and high-resolution satellite and aerial imagery has been previously used in a number of applications with regard to assessing vegetation presence, structure, biomass, and land cover change in riparian corridors (Johansen and Phinn 2006). To analyze how land cover has changed in the San Pedro River watershed over time, we performed a land cover classification of the binational San Pedro watershed for the year 2010. This land cover map provides an update to the existing series of four land cover maps (Kepner et al. 2000), which stretch across 24 years from 1973 to 1997. The land cover classification followed a sophisticated Classification and Regression Tree (CART) protocol that previously has shown success in producing high accuracy classifications in the nearby Santa Cruz watershed (Villareal et al. 2011). The final 2010 land cover map product (Figure 4) has an overall accuracy of 77.6%, which a review of the remote sensing literature found to be acceptably high, as 85% represents the highest accuracy possible with current methods. In comparison, the Kepner et al. (2000) land cover timeseries for the watershed utilized a combination of NASA Landsat MSS and TM imagery resampled to a 60m spatial resolution prior to classification. These classifications relied on the ISODATA procedure to perform an unsupervised classification. Overall accuracies for the four datasets (1973, 1986, 1992, and 1997) were assessed by Skirvin et al. (2004) and ranged from 68% to 75%. Due to the consistencies of the classification methodologies and type of imagery used, these four maps allow for a detailed quantitative examination of land cover change in both the United States and Mexican portions of the Upper San Pedro watershed for a 24 year span (Kepner et al. 2002).
CART Model Training and Reference Data

Training data were collected by digitally delineating polygons of homogeneous land cover for each class based on high spatial resolution basemap imagery made available by Environmental Systems Research Institute (ESRI) and 1-meter resolution imagery from the National Agriculture Imagery Program (NAIP) for 2010 (Table 1). Training data were collected across the entire extent of the watershed in order to capture the variance in elevation and slope gradients that occur across the watershed. During the development of the classification, several classes exhibited high variation, resulting in overestimation of occurrence. To improve classification accuracy, we split these classes into subclasses for training purposes. Urban was divided into high density and low density urban. Agriculture was split into three classes, corresponding to strong Normalized Difference Vegetation Index (NDVI) signals for (I) both scenes, (II) May only, and (III) September only. NDVI is an indicator of green leaf biomass, with higher values corresponding to higher amounts of green vegetation (Tucker 1979). These classes were recombined after the CART process was completed prior to any other post processing or execution of the accuracy assessment. A summary of the training data used to create the final land cover classification is presented in Table 2.

CART Model Input Data

The land cover classification methodology of the nearby Santa Cruz watershed performed by Villarreal et al. (2011) was used as a starting point for this classification of the Upper San Pedro watershed. See5, a data mining software (Quinlan 2012) was used in combination with ERDAS IMAGINE (Intergraph 2010) to construct the decision tree used in the CART process and to perform the classification. A key feature of the input data used to develop the
classification was the exploitation of the phenological changes resulting from the North American Monsoon (NAM). The NAM is marked by an increased amount of precipitation in the region during the summer months (Forzieri et al. 2011). The Upper San Pedro watershed, for example, receives approximately 65% of annual precipitation during the summer monsoon season, between July and September (Steinitz et al. 2003). Due to differences in the response to precipitation pulses (Hultine et al. 2004), different vegetation classes may experience varying levels of greening.

For the Upper San Pedro watershed, the phenological changes resulting from the NAM were striking (Figure 4). These changes were exploited using the multitemporal Kauth-Thomas (MKT) transformation, which shows differences in brightness, greenness, and wetness between dates (Collins and Woodcock 1996). Other layers used in the classification include Normalized Difference Vegetation Index (NDVI), which approximates the greenness of vegetation; Slope, derived from a 30m digital elevation model from the National Elevation Dataset (Gesch et al. 2002, Gesch 2007); and Band 3 (red) Texture, generated from a moving 3*3 standard deviation window on the Landsat imagery. The full list of input layers used in the final CART classification is presented in Table 3.

Post Processing

After the CART classification was completed, we manually examined the output dataset to identify areas of obvious misclassification. Many areas initially classified as Urban stood out as being incorrectly classified, especially dry streambeds that are spectrally similar to roads. The Automated Geospatial Watershed Assessment (AGWA) Tool’s Land Cover Modification Tool (Burns et al. 2004) was used to manually correct such areas of obvious misclassification. A majority filter with a 3*3 moving window was then used to reduce noise and create a smoother
classified surface. We also used the Smart Eliminate Tool from the NLCD Mapping Tools (Homer et al. 2007) to enforce a one-acre minimum mapping unit (five pixels).

Accuracy Assessment

A stratified random sampling approach was taken to perform the accuracy assessment of the 2010 land cover map. Strata were defined by the output land cover map, with 50 random accuracy assessment points per class, for a total of 500 points in accordance with recommendations of Congalton and Green (2008). During the accuracy assessment process, the identifying land cover information was not accessed. We manually identified each accuracy assessment site using the same ESRI basemap imagery and NAIP aerial photography used for training data collection. Due to potential georegistration errors between the Landsat and basemap imagery, only center pixels of 3*3 homogeneous areas of land cover were used as accuracy assessment sites. Areas covered by the training dataset were removed from consideration for the accuracy assessment. To ensure data objectivity and to remove any potential bias, a Python script was written to automatically generate and randomize the accuracy assessment sites. Final accuracies were assessed by analyzing overall accuracy, producer’s accuracy, user’s accuracy, and a kappa analysis (Story and Congalton 1986; Congalton and Green 2008).

Change Analysis

Comparing land cover change across a long data time series can yield valuable insights and understandings, though it is important to note limitations that can affect the level of confidence in comparison. For example, over a long time series, the spatial resolution of data inputs and methods of land cover classification are likely to change, as the spatial resolution of freely available remotely sensed imagery improves over time and new methodologies of
classification are developed. Here, we assess land cover change through two methods. First, we present a comparison of the relative proportions of each land cover class at the watershed scale and within the San Pedro Riparian National Conservation Area (SPRNCA) for each of the datasets. This method is used to assess broad trends in land use and land cover change over several decades, but has the disadvantage of not being spatially-explicit. Thus, it is not possible through this type of comparison to evaluate where the changes in land cover are occurring nor to assess the type of tradeoffs between land cover types. The second type of land cover change analysis presents the results of a post-classification change detection. This method of change detection demonstrates a spatially-explicit assessment of land cover change at both the regional, watershed scale and within the boundaries of the SPRNCA riparian conservation area.

The change detection analysis is particularly useful to assess the effectiveness of riparian conservation activities because it highlights specific areas of change on the landscape between the pair of years, 1986 (2 years before the establishment of the SPRNCA) and 2010 (22 years after the establishment of the SPRNCA). Assessing change within the established riparian conservation area over this 24-year time period provides valuable insight for locating areas of successful intervention in the riparian corridor, such as areas of increase in land cover types that are positive for riparian ecosystems, and for evaluating the specific conversions of one land cover type to another, such as the conversion of grassland to mesquite, which has been occurring in some areas of the SPRNCA.

**Results and Discussion**

*Accuracy Assessment*

We assessed the accuracy of the 2010 land cover classification using the well-established indicators of kappa analysis and overall, user’s, and producer’s accuracies. The accuracy
assessment results were organized into an error matrix (Table 4). Analysis of the error matrix revealed an overall accuracy of 77.60% and a kappa of 0.7511. Individual class accuracies varied from 53% to 100%, (Table 5). By comparison, Skirvin et al. (2004) reported an overall accuracy of 72% and a kappa of 0.65 for the 1997 land cover classification of the same area.

With an overall accuracy of 77%, the 2010 land cover map has a slightly higher accuracy than the maps created for the NALC project (Skirvin et al. 2004). The greatest single source of confusion came from areas of Oak Woodland misclassified as Forest (Table 4). Both communities are dominated by evergreen trees, with the primary difference coming from overall canopy cover and structure (Kepner et al. 2000). This level of detail may be difficult to discern at a 30m pixel resolution. Mesquite woodland had the lowest producer’s accuracy at 53%. The largest contribution to this was confusion with Grassland, possibly due to the influence of a largely grass understory in such areas. Another large source of error with Mesquite Woodland came with its misclassification as Riparian. The broad definition of Mesquite Woodland (crown coverage ≥15%; Kepner et al. 2000) is a likely culprit for why Mesquite Woodland is misclassified as both Grassland and Riparian areas, despite these classes being vastly different from one other. For the accuracy assessment of the prior NALC classification, Skirvin et al. (2004) had similar difficulties with Mesquite Woodland accuracies, attributing potential sources of error to insufficient spatial and spectral resolutions, as well as differences in interpretation among the groups performing the classification and accuracy assessment. Splitting the Mesquite Woodland into Mesquite Shrubland and Mesquite Bosque in future classifications could potentially improve overall classification accuracy. Barren had the lowest user’s accuracy (54%), with the largest confusion from Desertscrub. This confusion is understandable, as Desertscrub has sparse foliage surrounded by large amounts of barren ground. Likewise, the previous NALC
classifications also had difficulty with classifying Barren, notably having 0% accuracy (both user’s and producer’s) for the 1986 map (Skirvin et al. 2004).

Land Cover Change I: A Comparison of Relative Proportions of Land Cover Types

The updated land cover map we developed for the binational San Pedro River watershed for the year 2010 (Figure 5) demonstrates significant changes in land cover (Table 6). At the entire watershed scale, there has been a marked increase in urban cover and desert-scrub, accompanied by a decrease in cottonwood-willow riparian gallery forest, agriculture, and mesquite bosque. Grassland (35.50% of total land cover) and desert-scrub (35.32% of total land cover) were the dominant land covers in the Upper San Pedro River watershed, which is in line with the prior classifications of the watershed. Due to the improved spatial resolution of our 2010 classification (30-meters vs. 60-meters), the updated 2010 classification is able to detect major roads and dry riverbeds, two features that could not be discerned in the previous classifications. Throughout the watershed, urban cover has increased, particularly in the area around Sierra Vista. In contrast, agriculture has noticeably decreased, especially in the US portion of the watershed. Riparian areas have also decreased throughout the watershed, down to 26% of the

The 2010 classification reveals several trends in land cover changes that occurred throughout the watershed between the 1997 land cover map and our 2010 classification. In line with the general pattern of increasing urbanization in the Southwest (Steiner et al. 2000), particularly exurban, or “wildcat” development, there has also been a large increase in already existing urban areas. This trend is reflected in the growing populations of the urban centers in the watershed, such as the 16.2% population increase (6,113 people) in Sierra Vista seen between the 2000 and 2010 U.S. Census. Agriculture has seen a significant decrease, especially near
Benson, AZ and Sierra Vista, AZ, in line with observations by Steinitz et al. (2003). Another significant trend is a significant decline in Riparian areas. Though riparian vegetation decline from 1.91% in 1997 to 0.32% can potentially be linked to a number of factors, such as natural vegetation transitions or an improvement in the classification accuracy, it may also be indicative of a declining water table due to excessive groundwater pumping, which is a trend seen in the regional aquifer (Pool and Dickinson 2006). According to the class definition we used for classification, riparian cover is principally composed of cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*), which are both phreatophytic trees that require access to groundwater for their survival. If the groundwater table declines too rapidly or becomes too deep, widespread mortality of the riparian gallery forest may occur (Stromberg et al. 1996). Because the riparian gallery forest plays host to a wide array of critical ecosystem processes and functions (Stromberg and Tellman 2009), this apparent decline in the extent of the riparian corridor is cause for concern.

An interesting trend seen in comparisons between the old classifications and the new is the apparent decline in Mesquite Woodland from 13.41% in 1997 and 7.71% in 2010. Research on the persistence of woody plants (such as mesquite) and their dominance over herbaceous vegetation (Miller 2005) indicates that such a decline is unlikely to be related to an actual decrease in Mesquite Woodland on the ground. Analysis of the classification errors for the Mesquite Woodland class between the 1997 and 2010 classifications show similar producer’s accuracies (54% and 53%, respectively), but different user’s accuracies—48% in 1997, 80% in 2010. Because user’s accuracy refers to the probability that a classified pixel’s identity will correspond to the same class on the ground in reality (Story and Congalton 1986), the improvement in user’s accuracy and decline in coverage suggests the difference in Mesquite
Woodland coverage between 1997 and 2010 could be attributed to the large difference in reliability of the mapped Mesquite Woodland class in the 1997 classification versus the 2010 classification.

The addition of the 2010 classification provides an opportunity to analyze recent land use and land cover changes in the watershed at an enhanced level of detail. One application is looking at the impact of the establishment of the SPRNCA in 1988 (Table 7; Figure 6). The 1986 classification represents the pre-SPRNCA establishment conditions in the riparian corridor and the 2010 classification presents the riparian corridor condition two decades after SPRNCA. A long-term assessment of change in the SPRNCA has not previously been conducted. In the next section, we present the results of a spatially-explicit analysis of post-classification change detection that hones in on changes in riparian corridor land cover from 1986 to 2010.

*Land Cover Change II: Spatially-Explicit Post-Classification Change Detection*

The changes in land cover described across the watershed in the above section (4.2) have specific spatial distributions, which influence ecosystem function, water availability, and riparian health at the watershed scale and at the local riparian corridor scale. To assess the spatial location and distribution of significant land cover change, we conducted post-classification change detection between the 2010 and 1986 land cover maps, which allows for the comparison of classified land cover maps from different dates. Although the 2010 map and the previous land cover maps share an identical 10-class classification scheme, the spatial resolution of the images are not identical (60m v. 30m resolution). Thus, conducting change detection required that we re-scale the spatial resolution of the 2010 land cover classification to 60m, losing some of the image detail in the process.
The results of the change detection between the pair of years 1986 (pre-SPRNCA establishment) and 2010 (22 years post-SPRNCA establishment) are presented for riparian change (Figure 7, Table 8), agricultural change (Figure 8, Table 9), and urban change (Figure 9, Table 10). The northern portion of the watershed, near Fairbank, Arizona, has experienced significant decreases in agriculture in the river zone, while agriculture has increased along the international border and in the riparian zone in Sonora, on the land managed by the collective ranching community, Ejido María Morelos (Figure 8). Based on the results (Table 9), the transition away from agricultural land cover is dominated by three land cover classes that are replacing agriculture: desertscrub (26%), urban (25%), and grassland (23%). The largest increases in urban cover are visible in Arizona, encompassing both urban expansion of Sierra Vista and exurban, rural development, while Sonora remains highly rural and undeveloped with the exception of two urban centers, Naco and Cananea (Figure 9). A total of 3 percent of the pixels in the image changed to urban cover between 1986 and 2010, led by the conversion of grassland to urban cover (34%) and desertscrub to urban (33%) (Table 10).

Change in riparian cover is negative in almost all areas of the river (Figure 7, red color), with the exception of small areas of increased riparian forest cover on river tributaries (Figure 7, green color), and areas of no change (Figure 7, yellow color) within the SPRNCA boundaries. Only 0.22% of pixels in the image changed to riparian between 1986-2010 (Table 8), with 32% mesquite to riparian transition, 18% grassland to riparian transition, and 18% agricultural to riparian transition. The decrease in riparian cover presents a challenge to the success of establishing the SPRNCA. The largest land cover transition away from riparian was to mesquite cover (56%) (Table 8). However, the drivers of riparian change are multiple and complex and some of the change may also represent an improvement in the detail and classification accuracy.
of the 2010 map update, making it difficult to establish the influence of the conservation area on riparian change.

**Conclusion**

This research presents the results an updated land cover dataset for the binational San Pedro River watershed, bringing the temporal coverage of the entire time series to 37 years. The updated land cover map demonstrates significant changes in land cover. At the entire watershed scale, there has been a marked increase in urban cover and desert-scrub and a significant decrease in agriculture and riparian gallery forest. We find that the three land cover classes are replacing agriculture, specifically desert-scrub, urban, and grassland. Across almost all areas of the watershed, including much of the protected SPRNCA, riparian is decreasing with mesquite dominating the replacement land cover class as the riparian forest coverage retreats. These findings challenge the success of the SPRNCA as a riparian conservation strategy and raise important questions for resource managers about the drivers of the high spatial variability of riparian forest conservation.

Additionally, the updated land cover classification map and associated change detection analysis we present is significant because the spatially explicit assessment of change at multiple scales can be integrated into scenario planning, hydrological and ecological modeling, and local decision-making to inform natural resource policy and management, especially in regard to riparian conservation planning and post-conservation assessment of environmental restoration. In the transboundary U.S.-Mexico borderland region, achieving conservation goals is especially challenging and previous research confirms that it is imperative to understand and integrate decision-making across both sides of the international border. The availability of updated, transboundary, spatially-explicit datasets, such as the 2010 Upper San Pedro River watershed
land cover map, can assist in bringing together stakeholders from both sides of the border for integrated scenario-planning and decision-making that takes into account the distinct conservation and development interests across different geographic areas.
References


Figure 1. Map of the binational Upper San Pedro River watershed. The study area ranges from the headwaters of the river in Cananea, Sonora, Mexico to the USGS gaging station near Redington, Arizona. The white outline on the right-hand map denotes the San Pedro Riparian National Conservation Area (SPRNCA).
Figure 2: San Pedro River riparian corridor. Cottonwood-willow riparian canopy forest along a dry stretch of the once perennial San Pedro River within the SPRNCA (left hand photo); Wet stretch of the San Pedro River within the SPRNCA (right hand photo)
Figure 3: Time series of land cover maps for the San Pedro River watershed, 1973 to 2010 (Source: 1973-1997 maps, San Pedro Data Browser; 2010 map, by authors)
Figure 4. False color composite (FCC) images of May (left-hand image) and September (right-hand image) depicting the phenological change as a result of the summer monsoon in the Upper San Pedro watershed. Band 4 (near-infrared) is displayed as red, band 3 (red) as green, and band 2 (green) as blue. Green vegetation appears as shades of red.
Figure 5. Land cover map for the Upper San Pedro River watershed reflecting land cover conditions in 2010. The legend depicts the 10 land cover classes based on Kepner et al. (2000).
Figure 6. Land cover change in the SPRNCA. The 1986 panel displays conditions prior to the SPRNCA’s establishment (1988), while the 1997 and 2010 panels show how the landscape in and around the SPRNCA has changed since its establishment. Land cover classifications for 1986 and 1997 were created by Kepner et al. (2000).
Figure 7. Riparian change in the watershed, 1986-2010. Left image: Riparian land cover change at the watershed scale; Right image: Riparian land cover change within the SPRNCA. The areas highlighted in yellow represent no change in land cover class between the 1986 and 2010 images. The areas highlighted in green represent a shift to riparian land cover in the 2010 image from another land cover class type in the 1986 image. The areas highlighted in red represent a shift from riparian land cover in the 1986 image to another land cover class type in the 2010 image.
**Figure 8.** Agricultural change in the watershed, 1986-2010. Left image: Agricultural land cover change at the watershed scale; Right image: Agricultural land cover change within the SPRNCA. The areas highlighted in yellow represent no change in land cover class between the 1986 and 2010 images. The areas highlighted in green represent a shift to agriculture in the 2010 image from another land cover class type in the 1986 image. The areas highlighted in red represent a shift from agriculture in the 1986 image to another land cover class type in the 2010 image.
Figure 9. Urban change in the watershed, 1986-2010. Left image: Urban land cover change at the watershed scale; Right image: Urban land cover change within the SPRNCA. The areas highlighted in yellow represent no change in land cover class between the 1986 and 2010 images. The areas highlighted in green represent a shift to urban land cover in the 2010 image from another land cover class type in the 1986 image. The areas highlighted in red represent a shift from urban land cover in the 1986 image to another land cover class type in the 2010 image.
Table 1. Reference imagery used to collect training and accuracy assessment data for the 2010 land cover classification of the Upper San Pedro watershed.

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Table 2. Summary of the final training dataset used for the 2010 land cover classification of the Upper San Pedro watershed.

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Table 3. Input layers for the 2010 land cover classification of the Upper San Pedro watershed. All input layers were raster files (.img) in signed 16-bit format at a 30m spatial resolution. Landsat imagery and its derivatives were atmospherically corrected using ATCOR. Band 24 was eliminated during the winnowing process of developing the regression tree.

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Table 4. Error matrix for the 2010 land cover classification of the Upper San Pedro watershed. Overall accuracy is 77.60%, kappa 0.7511.

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Table 5. Individual class Producer’s and User’s accuracies, 2010 land cover classification

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<td>9. Water</td>
<td>100%</td>
<td>96%</td>
</tr>
<tr>
<td>10. Barren</td>
<td>87%</td>
<td>54%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class</th>
<th>1973 (%)</th>
<th>1986 (%)</th>
<th>1992 (%)*</th>
<th>1997 (%)*</th>
<th>2010 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>1.00</td>
<td>1.00</td>
<td>0.95</td>
<td>0.95</td>
<td>2.10</td>
</tr>
<tr>
<td>Oak Woodland</td>
<td>12.55</td>
<td>12.57</td>
<td>12.05</td>
<td>12.09</td>
<td>12.57</td>
</tr>
<tr>
<td>Mesquite</td>
<td>2.74</td>
<td>14.14</td>
<td>14.01</td>
<td>13.41</td>
<td>7.71</td>
</tr>
<tr>
<td>Grassland</td>
<td>41.35</td>
<td>35.28</td>
<td>34.57</td>
<td>34.81</td>
<td>35.50</td>
</tr>
<tr>
<td>Desertsrub</td>
<td>38.99</td>
<td>32.11</td>
<td>31.25</td>
<td>30.26</td>
<td>35.32</td>
</tr>
<tr>
<td>Riparian</td>
<td>1.14</td>
<td>0.82</td>
<td>0.85</td>
<td>1.21</td>
<td>0.32</td>
</tr>
<tr>
<td>Agriculture</td>
<td>1.15</td>
<td>1.80</td>
<td>2.40</td>
<td>1.91</td>
<td>0.66</td>
</tr>
<tr>
<td>Urban</td>
<td>0.45</td>
<td>1.36</td>
<td>1.65</td>
<td>2.22</td>
<td>4.05</td>
</tr>
<tr>
<td>Water</td>
<td>0.04</td>
<td>0.01</td>
<td>0.05</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Barren</td>
<td>0.60</td>
<td>0.91</td>
<td>0.94</td>
<td>0.92</td>
<td>1.74</td>
</tr>
</tbody>
</table>

[*1.28% and 2.15% cloud cover in predominantly Forest and Oak Woodland areas (1992 and 1997 classifications, respectively)*]
Table 7. Proportional land cover change over time within the SPRNCA.

<table>
<thead>
<tr>
<th>Land Cover Class</th>
<th>1986</th>
<th>1997</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesquite Woodland</td>
<td>21%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Grassland</td>
<td>17%</td>
<td>16%</td>
<td>34%</td>
</tr>
<tr>
<td>Desertscrub</td>
<td>44%</td>
<td>41%</td>
<td>46%</td>
</tr>
<tr>
<td>Riparian</td>
<td>12%</td>
<td>14%</td>
<td>3%</td>
</tr>
<tr>
<td>Agriculture</td>
<td>7%</td>
<td>6%</td>
<td>0%</td>
</tr>
<tr>
<td>Urban</td>
<td>1%</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Barren</td>
<td>0%</td>
<td>0%</td>
<td>3%</td>
</tr>
</tbody>
</table>
Table 8. Results of the post-classification change detection for “change to” riparian and “change from” riparian, 1986 to 2010.

<table>
<thead>
<tr>
<th>Change Type</th>
<th>Number of Pixels</th>
<th>Percent of Total</th>
<th>Percent of Total Riparian Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total change to Riparian:</strong></td>
<td>4739</td>
<td>0.2242</td>
<td></td>
</tr>
<tr>
<td>From Forest to Riparian</td>
<td>33</td>
<td>0.0016</td>
<td>0.6963</td>
</tr>
<tr>
<td>From Oak to Riparian</td>
<td>1007</td>
<td>0.0476</td>
<td>21.2492</td>
</tr>
<tr>
<td>From Mesquite to Riparian</td>
<td>1551</td>
<td>0.0734</td>
<td>32.7284</td>
</tr>
<tr>
<td>From Grassland to Riparian</td>
<td>882</td>
<td>0.0417</td>
<td>18.6115</td>
</tr>
<tr>
<td>From Desertscrub to Riparian</td>
<td>270</td>
<td>0.0128</td>
<td>5.6974</td>
</tr>
<tr>
<td>From Agriculture to Riparian</td>
<td>858</td>
<td>0.0406</td>
<td>18.1051</td>
</tr>
<tr>
<td>From Urban to Riparian</td>
<td>94</td>
<td>0.0044</td>
<td>1.9835</td>
</tr>
<tr>
<td>From Water to Riparian</td>
<td>9</td>
<td>0.0004</td>
<td>0.1899</td>
</tr>
<tr>
<td>From Barren to Riparian</td>
<td>35</td>
<td>0.0017</td>
<td>0.7386</td>
</tr>
<tr>
<td><strong>Total change from Riparian:</strong></td>
<td>15384</td>
<td>0.7278</td>
<td></td>
</tr>
<tr>
<td>From Riparian to Forest</td>
<td>5</td>
<td>0.0002</td>
<td>0.0325</td>
</tr>
<tr>
<td>From Riparian to Oak</td>
<td>85</td>
<td>0.0040</td>
<td>0.5525</td>
</tr>
<tr>
<td>From Riparian to Mesquite</td>
<td>8718</td>
<td>0.4124</td>
<td>56.6693</td>
</tr>
<tr>
<td>From Riparian to Grassland</td>
<td>3180</td>
<td>0.1504</td>
<td>20.6708</td>
</tr>
<tr>
<td>From Riparian to Desertscrub</td>
<td>800</td>
<td>0.0378</td>
<td>5.2002</td>
</tr>
<tr>
<td>From Riparian to Agriculture</td>
<td>579</td>
<td>0.0274</td>
<td>3.7637</td>
</tr>
<tr>
<td>From Riparian to Urban</td>
<td>920</td>
<td>0.0435</td>
<td>5.9802</td>
</tr>
<tr>
<td>From Riparian to Water</td>
<td>19</td>
<td>0.0009</td>
<td>0.1235</td>
</tr>
<tr>
<td>From Riparian to Barren</td>
<td>1078</td>
<td>0.0510</td>
<td>7.0073</td>
</tr>
<tr>
<td><strong>No change:</strong></td>
<td>1976</td>
<td>0.0935</td>
<td></td>
</tr>
</tbody>
</table>
Table 9. Results of the post-classification change detection for “change to” agriculture and “change from” agriculture, 1986 to 2010.

<table>
<thead>
<tr>
<th>Change Type</th>
<th>Number of Pixels</th>
<th>Percent of Total</th>
<th>Percent of Total Ag. Change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total change to Agriculture:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From Forest to Agriculture</td>
<td>21</td>
<td>0.0010</td>
<td>0.2414</td>
</tr>
<tr>
<td>From Oak to Agriculture</td>
<td>433</td>
<td>0.0205</td>
<td>4.9770</td>
</tr>
<tr>
<td>From Mesquite to Agriculture</td>
<td>2164</td>
<td>0.1024</td>
<td>24.8736</td>
</tr>
<tr>
<td>From Grassland to Agriculture</td>
<td>3579</td>
<td>0.1693</td>
<td>41.1379</td>
</tr>
<tr>
<td>From Desertsrub to Agriculture</td>
<td>1387</td>
<td>0.0656</td>
<td>15.9425</td>
</tr>
<tr>
<td>From Riparian to Agriculture</td>
<td>579</td>
<td>0.0274</td>
<td>6.6552</td>
</tr>
<tr>
<td>From Urban to Agriculture</td>
<td>453</td>
<td>0.0214</td>
<td>5.2069</td>
</tr>
<tr>
<td>From Water to Agriculture</td>
<td>20</td>
<td>0.0009</td>
<td>0.2299</td>
</tr>
<tr>
<td>From Barren to Agriculture</td>
<td>64</td>
<td>0.0030</td>
<td>0.7356</td>
</tr>
<tr>
<td><strong>Total change from Agriculture:</strong></td>
<td><strong>32879</strong></td>
<td><strong>1.5554</strong></td>
<td></td>
</tr>
<tr>
<td>From Agriculture to Forest</td>
<td>18</td>
<td>0.0009</td>
<td>0.0547</td>
</tr>
<tr>
<td>From Agriculture to Oak</td>
<td>185</td>
<td>0.0088</td>
<td>0.5627</td>
</tr>
<tr>
<td>From Agriculture to Mesquite</td>
<td>4367</td>
<td>0.2066</td>
<td>13.2820</td>
</tr>
<tr>
<td>From Agriculture to Grassland</td>
<td>7724</td>
<td>0.3654</td>
<td>23.4922</td>
</tr>
<tr>
<td>From Agriculture to Desertsrub</td>
<td>8653</td>
<td>0.4093</td>
<td>26.3177</td>
</tr>
<tr>
<td>From Agriculture to Riparian</td>
<td>858</td>
<td>0.0406</td>
<td>2.6096</td>
</tr>
<tr>
<td>From Agriculture to Urban</td>
<td>8427</td>
<td>0.3987</td>
<td>25.6303</td>
</tr>
<tr>
<td>From Agriculture to Water</td>
<td>120</td>
<td>0.0057</td>
<td>0.3650</td>
</tr>
<tr>
<td>From Agriculture to Barren</td>
<td>2527</td>
<td>0.1195</td>
<td>7.6858</td>
</tr>
<tr>
<td><strong>No change:</strong></td>
<td><strong>5184</strong></td>
<td><strong>0.2452</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table 10. Results of the post-classification change detection for “change to” urban and “change from” urban, 1986 to 2010.

<table>
<thead>
<tr>
<th></th>
<th>Number of Pixels</th>
<th>Percent of Total</th>
<th>Percent of total Urban Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Count of pixels:</td>
<td>2113841</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total change to Urban:</td>
<td>66991</td>
<td>3.1692</td>
<td>0.0104</td>
</tr>
<tr>
<td>From Forest to Urban</td>
<td>7</td>
<td>0.0003</td>
<td>0.0104</td>
</tr>
<tr>
<td>From Oak to Urban</td>
<td>1756</td>
<td>0.0831</td>
<td>2.6212</td>
</tr>
<tr>
<td>From Mesquite to Urban</td>
<td>10208</td>
<td>0.4829</td>
<td>15.2379</td>
</tr>
<tr>
<td>From Grassland to Urban</td>
<td>22751</td>
<td>1.0763</td>
<td>33.9613</td>
</tr>
<tr>
<td>From Desertscrub to Urban</td>
<td>22183</td>
<td>1.0494</td>
<td>33.1134</td>
</tr>
<tr>
<td>From Riparian to Urban</td>
<td>920</td>
<td>0.0435</td>
<td>1.3733</td>
</tr>
<tr>
<td>From Agriculture to Urban</td>
<td>8427</td>
<td>0.3987</td>
<td>12.5793</td>
</tr>
<tr>
<td>From Water to Urban</td>
<td>12</td>
<td>0.0006</td>
<td>0.0179</td>
</tr>
<tr>
<td>From Barren to Urban</td>
<td>727</td>
<td>0.0344</td>
<td>1.0852</td>
</tr>
<tr>
<td>Total change from Urban:</td>
<td>10056</td>
<td>0.4757</td>
<td></td>
</tr>
<tr>
<td>From Urban to Forest</td>
<td>2</td>
<td>0.0001</td>
<td>0.0199</td>
</tr>
<tr>
<td>From Urban to Oak</td>
<td>498</td>
<td>0.0236</td>
<td>4.9523</td>
</tr>
<tr>
<td>From Urban to Mesquite</td>
<td>957</td>
<td>0.0453</td>
<td>9.5167</td>
</tr>
<tr>
<td>From Urban to Grassland</td>
<td>4898</td>
<td>0.2317</td>
<td>48.7072</td>
</tr>
<tr>
<td>From Urban to Desertscrub</td>
<td>2719</td>
<td>0.1286</td>
<td>27.0386</td>
</tr>
<tr>
<td>From Urban to Riparian</td>
<td>94</td>
<td>0.0044</td>
<td>0.9348</td>
</tr>
<tr>
<td>From Urban to Agriculture</td>
<td>453</td>
<td>0.0214</td>
<td>4.5048</td>
</tr>
<tr>
<td>From Urban to Water</td>
<td>9</td>
<td>0.0004</td>
<td>0.0895</td>
</tr>
<tr>
<td>From Urban to Barren</td>
<td>426</td>
<td>0.0202</td>
<td>4.2363</td>
</tr>
<tr>
<td>No change:</td>
<td>18641</td>
<td>0.8819</td>
<td></td>
</tr>
</tbody>
</table>