FACTORS INFLUENCING RESTORATION SUCCESS OF ABANDONED AGRICULTURAL FIELDS ON THE LOWER SAN PEDRO RIVER TERRACES, SOUTHEASTERN ARIZONA

A Thesis
by
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ABSTRACT

FACTORS INFLUENCING RESTORATION SUCCESS OF ABANDONED AGRICULTURAL FIELDS ON THE LOWER SAN PEDRO RIVER TERRACES, SOUTHEASTERN ARIZONA. (August 2011)

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Abandonment of agricultural fields is a common occurrence worldwide. Natural recovery, or succession, often occurs following land abandonment. However, in arid regions succession may not occur and active restoration techniques are sometimes used to facilitate native vegetation growth. Along the lower San Pedro River in southeastern Arizona, restoration projects have resulted in mixed success. Though some fields have responded to restoration treatments, others have not. Abiotic and biotic factors likely affecting restoration outcomes in this arid environment include soil conditions, restoration treatments, and seed availability.

Predictor variables were examined to identify which environmental factors most influenced vegetation characteristics of abandoned agricultural fields on river terraces. To do this, GIS-based site suitability analysis was used to identify abandoned agricultural fields, and field data were collected in 20 fields. Woody stem density, basal area, and elevation were recorded in three 100 m^2 study plots in each field. Soil samples were collected and pH, particle size analysis, and electrical conductivity of saturated soil paste were performed.

In addition, environmental variables were collected at the field scale within a GIS. These variables included field area, distance to upland and terrace vegetation, and field distance to the San Pedro River. Management data were collected from landowners and managers about each of the 20 field sites, including number of years each field was farmed, time since abandonment, and whether restoration treatments such as planting/seeding, irrigation, grazing, or mowing were employed.

Analysis of woody vegetation showed field sites had low woody basal area and low woody stem density. Low woody species richness was also observed and *Prosopis velutina* was the dominant species at field sites. Field distance to terrace and upland vegetation was variable, but never more than 0.5 km away. Soil pH tests showed alkaline soil conditions, and electrical conductivity of soil samples revealed medium to high soil salinity levels. Soils were predominately of a sand and silt texture. Management information described a long history of cultivation at sites, involving a decade or more of agricultural use at each field site.

Two regression models were created, one for woody basal area and one for woody stem density. All fourteen soil, field, and management/history variables were entered into each model. Significant predictors of woody basal area included distance to terrace vegetation, percent clay in the soil, and post planting and/or seeding treatment. Significant predictors of woody stem density included field area, years farmed, and time (years) since abandonment. ANOVAs determined that restoration management treatments were generally not associated with significant increases in woody stem density, woody basal area, or percent herbaceous cover. Ultimately, the factors limiting restoration were complex and interconnected. However, the findings of this project point toward lingering agricultural legacies impeding restoration efforts.

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CHAPTER I

INTRODUCTION

Abandonment of agricultural fields is a common occurrence worldwide. Such land use change has been a major catalyst for environmental change throughout the world (Vitousek, 1994; Wong et al., 2010). Hobbs and Cramer (2007) describe a mix of social, economic, and ecological factors as the causes of field abandonment. Socioeconomic factors include the depopulation of rural areas, and technological advances in farming, resulting in declines in the use of traditional farming techniques. Ecological factors include the degradation of land by overgrazing or inappropriate agricultural practices, desertification, or global climate change, (Hobbs and Cramer, 2007; Verstraete et al., 2009).

On a global scale, abandoned cropland has significantly increased. From 1870 to present time, abandonment has grown exponentially from approximately 10 million hectares to 210 million hectares (Ramankutty and Foley, 1999). Following the industrial revolution, urbanization and industrialization in the U.S. caused more rapid abandonment of agricultural lands than in previous times. Specifically, in the Western U.S. the rate of abandonment reached high levels in the 1940s and those rates continued until about 1997 (Waisanen and Bliss, 2002). Rapid abandonment of agricultural lands presents land managers and researchers with a significant challenge. This is because ecosystems are dynamic, and interactions between factors such as disturbance and climate can make vegetation in ecosystems difficult to predict and manage (Peters and Havstad, 2006). However, this challenge is a unique opportunity for managers to improve degraded sites and restore native vegetation through use of appropriate management techniques.

In this chapter, I first discuss the significance of restoration. I will also make connections between ecological successional theory and restoration. Next, I will narrow my focus to arid region restoration, and will elaborate on the limiting factors of particular significance to arid region restoration. Then, I will investigate how GIS can be used as a tool in aiding restoration efforts, particularly arid restoration, through the use of site suitability analyses. Finally, I will elaborate on the history of the study area (the San Pedro River, Arizona, USA) and outline the objectives for this study.

a. Restoration and Succession

Restoration defined and its significance

Restoration of abandoned agricultural fields has become an important and increasingly popular conservation strategy in recent times. The practice of restoration involves manipulating a system to achieve an end goal, such as improvement of ecosystem services or biodiversity (SER, 2004). However, restoration projects are conducted for many reasons. For example, Zerbe (2002) and Wenhua (2004) described projects in which restoration was implemented to meet economic goals of sustainable forestry. When used for conservation, restoration can have a positive effect by restoring native species and habitats, as well as protecting the habitats of endangered species (Bakker and Berendse, 1999). This is especially important in habitats used by imperiled species. For example, in the southwestern U.S., the Southwestern Willow Flycatcher (*Empidonax traillii extimus*) is an endangered bird that depends on riparian vegetation for habitat, including vegetation patches dominated by the non-native species saltcedar (*Tamarix ramosissima*) in the San Pedro region (USFWS, 2002; Harms and Hiebert, 2006; Katz et al., 2009a). All endangered species need habitat to survive, and restoring Southwestern Willow flycatcher habitat is critical to the species' existence and to promoting biodiversity in the San Pedro River corridor.

Restoration can be passive or active in nature. Passive restoration usually involves modification of existing management activities (Hemstrom et al., 2002; Shinneman et al., 2008), or removal of stressors (Katz et al., 2009b), but does not involve restoration treatments (Zafra-Calvo et al., 2010). For example, Zafra-Calvo et al. (2010) created a plan that used passive restoration as a primary means for conservation on the island of Bioko in Equatorial Guinea, Africa. There, they allowed abandoned cocoa plantations to re-vegetate as part of a strategic conservation plan. This action helped connect fragmented habitats by using newly vegetated fields as "stepping stones" to the original habitat, thus promoting biodiversity bridges on Bioko. On the San Pedro River in Arizona, Katz et al. (2009b) used reference sites to target appropriate restoration conditions. In the study, groundwater pumping was reduced, and the river ecosystem was given the opportunity to recover unassisted.

Active restoration is often needed to achieve conservation goals when ecosystems do not recover unassisted or through passive means (Suding et al. 2004). Active restoration methods involve direct human intervention to assist the vegetation recovery process by applying treatments that might influence recovery (Hemstrom et al., 2002). A range of treatments can be used, such as planting/seeding, grazing, controlled fire, or fertilizer treatment (Hemstrom et al., 2002; Shinneman et al., 2008). For example, Richter and Stutz

(2002) planted *Sporobolus wrightii* (big sacaton grass) in pots and then transplanted the plants to abandoned fields in Arizona, USA. At a restoration site in Cape Floristic Kingdom, South Africa, Holmes (2001) used seed mix and fertilizing treatments to recruit native shrub species at restoration sites. Similarily, Menke (1992) explained how researchers used grazing and prescribed burning as restoration tools at the Hopland Field Station and at the Jepson Prairie in California, USA. They found that short-term high-intensity grazing could increase the abundance of native perennial grasses at experimental sites. They also found that prescribed burning helped increase native grass growth by lowering competition from other plants. Thus, both passive and active restoration have been used successfully in a variety of contexts to meet conservation goals.

Succession concepts

Succession is a central concept that drives the theories and practice of restoration (Hobbs et al., 2007b). Succession is relevant to restoration because successional processes can return ecosystems back to previous vegetation conditions (Suding et al., 2004). Ecological succession can be defined most simply as habitat or species change over time (Hobbs et al., 2007a). Succession and thresholds are connected, in that succession often involves ecosystem change, and ecosystem change and disturbance can initiate thresholds to be crossed (Suding and Hobbs, 2008). Thresholds can be characterized as occurring when an ecosystem rapidly changes in response to a condition or driver, causing a regime shift (Cramer at al., 2008). Thresholds help explain how succession is triggered as they determine when ecosystem change might occur. However, thresholds are difficult to quantify, and often are not recognized until they are crossed (Hobbs et al., 2007a).

Successional theory is important to consider in the context of restoration because it helps us understand ecosystem change, how and why it might occur, and how restoration might facilitate that change to a more desirable state. Succession and restoration are unifying concepts because restoration addresses and attempts to manipulate ecosystem change. The concept of succession was first associated with Clements (1916), who proposed a linear equilibrium model. Clements (1916) described plant succession as a process in which vegetation developed from initial bare land, first inhabited by a few pioneer species, to a final stable, climax state through six linear stages: nudation, migration, ecesis, competition, reaction, and finally, stabilization. Under Clement's (1916) theory, in abandoned agricultural fields succession occurs in a predictable pattern of vegetation recovery from grassland to forest (Wong et al., 2010).

Gleason (1939) believed that succession did not occur in a linear manner, but that succession occurred in a random or stochastic manner. Stochastic dynamics suggests that random development of an ecosystem affects successional patterns in a non-linear manner (Gleason, 1939; Hobbs et al., 2007a). Following Gleason's (1939) stochastic successional theories, other stochastic models emerged from the field of ecology. Margalef (1968) and Odum (1969) argued that succession is stochastic, but that it always moves an ecosystem towards higher biomass and biodiversity. Though succession could occur in a random manner through stochastic dynamics, all these theories held the common belief that ecosystems always move towards a final state (Hobbs and Walker, 2007).

Although restoration can be viewed as a process of manipulating successional outcomes (Suding et al., 2004), addressing and manipulating vegetation dynamics is often difficult. For example, abandoned agricultural fields frequently have a low ecological resilience, meaning that they return to their former state very slowly (Suding et al., 2004; Standish et al., 2007). Positive feedbacks, which can help re-enforce a process or change contribute to an ecosystem's resilience, which can be defined as the ability or speed of an ecosystem to return to a previous (native or desirable) state (Suding et al., 2004). Sometimes, fields will remain in a persistent and degraded state, which can be defined as when an ecosystem requires treatments and will not restore itself otherwise (Suding et al., 2004; Suding et al., 2007).

In succession, multiple stable states can exist (Suding et al., 2004). Many times, old fields, or abandoned farmland (Hobbs and Cramer, 2007), will become stuck in alternative stable states, meaning the area or ecosystem will persist in different combinations of states and environmental conditions than what one might expect to find (Suding et al., 2004). This can be defined as when a threshold is passed, the trajectory of a system changes to a state that is or is not a desired state (Suding and Hobbs, 2009). For example, a system may no longer be able to sustain previous historical vegetation, and may instead sustain other types of vegetation, including non-native species, as a result of significant disturbance like agriculture (Suding et al., 2004). Often, a feedback loop will cause lands to stay in this state unless restoration techniques are used (Suding and Hobbs, 2009). One prominent example of this is in Australia, where revegetation of abandoned wheat fields has been slow, showing almost no change 45 years after abandonment (Standish et al., 2007).

Additionally, in rangeland and arid restoration literature, researchers have moved towards non-equilibrium models (Bestelmeyer et al., 2003). For example, Bestelmeyer et al. (2006) assessed restoration in arid environments using state and transition models. State and transition models assume that development occurs in stages, and that disturbance drives an ecosystem to change from one state to another (Hobbs et al., 2007a). Often, these are set up in a flowchart manner in which transitions among states are visualized, assuming ecosystem change does not move toward one particular state, but moves toward different states (Suding and Hobbs, 2008). Specific processes described for each discreet state are what cause transitional change (Bestlemeyer et al., 2003; Suding and Hobbs, 2009).

To understand how to best implement restoration techniques, successional theory and restoration practice should take a unifying approach (Suding and Hobbs, 2009). Suding and Hobbs (2009) argued that we need to connect threshold dynamics and theory with the actual implementation of restoration techniques. Suding and Hobbs (2009) argued that models that are developed in collaboration with researchers, managers, and stakeholders are most effective at guiding restoration. They stated that the most effective approaches might lie in methods that look at the problem through a combination of theory and practice. A call to action is occurring in the restoration literature, particularly by Suding and Hobbs (2009), as some are realizing that a holistic approach involving theory and application must be used in restoration.

b. Global restoration

Examples of restoration and relevance to arid region restoration

In looking at studies in many countries, it is apparent that restoration has an economic and ecological value in the world today, as studies involving succession and restoration have been popular in humid temperate climates worldwide. For example, Zerbe (2002) examined restoration of broad-leaved woodlands to promote sustainable forestry in Europe, where coniferous forests were planted during the industrial revolution. Wenhua (2004) explained how the Chinese government established the National Forest Conservation Programme (NFCP), a group that since 1998 has worked to restore natural forests for sustainable forestry purposes in China.

Unlike these humid temperate studies though, there is concern over unsuccessful restoration in arid regions, namely slow vegetation recovery (Cramer et al., 2007). This is because restoration in arid regions often does not abide by typical, broadly repeatable trajectories of recovery. Instead, arid region restoration sites might linger in a persistent degraded state, struggling to recover even on a decadal time scale (Cramer et al., 2007). One study that was performed in a harsh climate is that of Sarmiento et al. (2003), who examined restoration and succession patterns of agricultural plots in the Paramo, an alpine ecosystem in Paramo de Gavidia, Sierra Nevada National Park, located in the Venezuelan Andes. Although not in an arid region, this study is insightful because some of the same problems persist, such as agricultural fields that will not respond to treatments, a history of agriculture, and soils that are limited by climatic factors.

c. Agricultural legacies

In abandoned agricultural fields in arid regions, the legacy of past land use is probably the most significant factor causing the ecosystem to remain in a degraded state. This is because arid region abandoned fields have often crossed both abiotic and biotic thresholds, causing these fields to be unable to recover without assistance (Cramer et al., 2008). Agricultural legacies may be so strong that the effects of agricultural land use persist for decades (Standish et al., 2006; Wong et al., 2010). Manipulation of the soils and alteration of seed banks have likely caused these fields to have long, enduring agricultural legacies.

Agricultural legacies and their effects on ecosystems are frequently mentioned in restoration literature (Sarmiento et al., 2003; Cramer et al. 2007; Cramer et al., 2008). For example, Cramer et al. (2008) discussed the ecological theories behind enduring agricultural legacies in three fields: one in Michigan, USA, one in Costa Rica, and another in southwest Western Australia. These three fields provided examples of a field entering succession soon after abandonment (Michigan, USA), a field with a delayed successional trajectory (Costa Rica), and finally, a field remaining in a degraded state with little to no recovery (southwest Western Australia). Discussion of field recovery focused on why the arid field in Australia had not recovered, due to abiotic and biotic interactions. In another study, Cramer et al. (2007) found that historical agricultural practices were the primary cause of land degradation in Western Australia. Specifically, they found that that the overuse of superphosphate fertilizers and herbicides, extensive tillage, and frequent planting were to blame. Sarmiento et al. (2003) found that fallow agriculture was negatively affecting ecosystem succession in the Venezuelan Andes. They also found that fallow plots persisted in a state of lower species richness and required vegetation recovery efforts. These findings provide valuable insights into the problem of lingering agricultural legacies on abandoned fields in general, as well as in arid regions.

d. Factors influencing ecological restoration in arid regions

Researchers study vegetation in arid climates to better understand the complex factors affecting restoration and successional outcomes (Peters and Havstad, 2006; Cramer et al., 2007; Munro et al., 2009). Addressing the factors impeding restoration is important, especially in deserts where conditions are harsh and resources are limited. Abiotic and biotic factors can impede restoration attempts in arid locations (Webb and Leake, 2006; Cramer et al., 2007). Though some fields appear to have responded to restoration treatments, others have resisted restoration (Cramer et al., 2007). This is because ecosystems are dynamic—thus, there are many factors that can influence restoration outcomes, such as seed source, soils, and environmental factors.

Vegetation factors: seed availability

Biotic variables, such as seed dispersal, can influence field recovery. For example, distance to seed source, combined with a limited local seed bank caused by long-term agriculture, are primary biotic factors that can greatly influence recovery on arid abandoned fields (Cramer et al., 2007). Seed dispersal is important for the establishment and continued persistence of a plant community, because plants must be able to colonize an area and produce seeds, and when distance impedes this action, plant communities will not establish. One significant way in which seeds disperse is through animal transport, as animals foraging for food can disperse seeds in several ways. Seeds can attach to their bodies by means of hooks or barbs, and animals can disperse them via digestion (Soykan et al., 2009). Seeds are able to disperse large distances by way of animal transport, often times as much as 1 km (Bakker et al., 1996). According to Bakker et al. (1996), wind dispersal occurs in almost all plant species, and weight and size of the seed largely determines the distance seeds can travel. This is because seeds of woody plants are often large, and unless water or animal dispersal occurs, seeds might be too heavy to travel significant distances by wind.

Many factors can keep seeds from developing into seedlings and subsequently establishing at sites. One factor is the number of seeds available, which directly affects the rate of recruitment of seedlings and the success of maintaining a plant community (van der Valk, 1992). Factors affecting the number of seeds include environmental conditions at the site, presence of pollinators, and predation of plants just before seed dispersal (van der Valk, 1992). Seed predation by animals, particularly rodents, can also influence seed dispersal and contribute to seed mortality (Collins and Uno, 1985). Another factor is seed germination and establishment, which is also important to consider. Factors altering seed germination include soil moisture, light, temperature, and oxygen availability at the time of germination (van der Valk, 1992).

Additionally, if environmental conditions are not appropriate at the time the seed is dispersed, seeds can remain dormant until suitable conditions arise. Viable seeds that remain dormant contribute to an ongoing seed bank, found in the soil (Shaukat and Siddiqui, 2004). By retaining viable seeds until they are able to sprout, seed banks can have positive or negative consequences. One positive consequence is that seeds that have not been eaten by animals that are still present in the seed bank can eventually contribute to the vegetation of a site, increasing the ecosystem's resilience (Suding et al., 2004). However, if the seed bank is altered, native vegetation might not return to fields because conditions are not suitable, or native seeds no longer exist in the seed bank (Shaukat and Siddiqui, 2004).

Soils

Soil conditions can have significant impacts on restoration efforts in arid environments (Webb and Leake, 2006; Menninger and Palmer, 2006; Cramer et al., 2008).

For example, in the Mediterranean region, poor soil conditions caused by historical agricultural land use hindered vegetation growth on restoration sites (Ruiz-Navarro et al., 2009). Low precipitation and high evapotranspiration in the area (arid to semi-arid climate) can enable wetting-drying action in the soil that causes an accumulation of salts and increased soil salinity (Buol et al., 2003), possibly impeding vegetation recovery (Green et al., 2009). In addition, agricultural irrigation could have adversely affected soils by increasing the soils salinity or pH, negatively impacting conditions for recovery. Additionally, soil texture may affect restoration outcomes (Beauchamp and Shafroth, 2011). For example, Beauchamp and Shafroth (2011) found soil texture to be a significant predictor of certain plant communities in reference sites in New Mexico, USA. The soil texture-plant community relationship could be related to a change in water availability, caused by the clayey soil texture.

Environmental conditions

Environmental factors such as climatic patterns and hydrologic conditions could have significant impacts on restoration efforts in arid environments (Webb and Leake, 2006; Menninger and Palmer, 2006; Cramer et al., 2008). For example, Peters and Havstad (2006) discussed climate as one factor impeding restoration in southern New Mexico, USA. Specifically, they found that drought and climatic patterns influenced management outcomes in these arid ecosystems.

Depth to groundwater could be another limiting factor affecting riparian restoration in arid regions. This is because rate of change of groundwater depth is an important factor in determining survival of riparian and other vegetation near the San Pedro River (Shafroth et al., 2000; Webb and Leake, 2006). Depth to groundwater is often affected by groundwater pumping (Webb and Leake, 2006). For example, Webb and Leake (2006) observed that when water is pumped rapidly or over long periods of time a cone of depression will develop around a well. They found that when this area is near a floodplain, the quick lowering of water will kill nearby trees in a matter of days. However, they found that in periods of drought or slow, steady pumping, sometimes plants and trees are able to lengthen their roots in response to lowered groundwater conditions. This is important to recognize because slow impacts on a system could be much less detrimental than rapid pumping, which can occur in response to urbanization and population growth. Furthermore, groundwater pumping could lead to stress and decreased moisture conditions for vegetation on floodplains (Beauchamp and Shafroth, 2011).

e. GIS used for site-suitability analysis and site identification

Site suitability analysis is used to determine the most appropriate spatial area for a particular activity, and is often used for planning purposes (Malczewski, 2004). Site suitability analysis for ecological purposes began when Ian McHarg used transparent acetate papers to perform a complex overlay of many different environmental and anthropogenic attributes over a selected site in the late 1960s (McHarg, 1969). McHarg's (1969) seminal work was important to planners and ecologists alike; he was the first to develop an ecological inventory process for use in his analog site suitability analysis. With the contributions of map algebra and cartographic modeling, pioneered in early GIS by Dana Tomlin (Tomlin, 1990) and Joe Berry (Berry, 1993), GIS has become a powerful and efficient analysis tool, particularly in site suitability studies (Malczewski, 2004). GIS software has made it possible to input digital data layers, apply relevant criteria, and perform site suitability analysis to solve a complex problem.

Since the early 1990s, site suitability analysis has been applied in in a variety of research applications. For example, researchers have focused on using site suitability studies to determine the most suitable locations for retail establishments (Benoit and Clarke, 1997), or for landscape and urban planning uses (Miller et al., 1998). This type of analysis has also been successfully used in agricultural applications and environmental impact assessments (Malczewski, 2004). Site-suitability has also been used to solve ecological, conservation, and restoration issues, such as when Braunisch and Suchant (2008) used a site-suitability analysis for wildlife conservation, where vegetation structure and soils were the defining criteria. Malmstrom et al. (2008) identified sites and quantified the effects of seeding restoration efforts in a California rangeland. In their study, they used GIS and remote sensing techniques to compare old fields using historical Landsat imagery. Rohde et al. (2006) used multiple limiting criteria to produce a site-suitability analysis for river floodplain restoration in Switzerland. In this study, they used filters to determine restoration criteria, including contraints such as slope steepness and built-up area, ecological suitability factors such as hydrology and biodiversity, and socioeconomic factors such as flood protection and infrastructure. Thus, Rohde et al. (2006) provided an effective and significant contribution to GIS site suitability literature because they used a large number of criteria to identify river reaches most suitable for restoration, focusing on ecology as well as human needs.

f. Study area: the San Pedro River

The San Pedro River is located in southeastern Arizona, and the river headwaters originate in northern Mexico. The lower San Pedro River contains perennial, ephemeral, and intermittent steam reaches, and is unmodified from its natural course (Stromberg et al., 2005). Relief is low in the San Pedro River valley and terraces are flat, though terraces sit at a higher surface level than the river channel and are hydrologically drier because of their height above the groundwater table (Stromberg, 1993). The climate of the San Pedro River basin is semi-arid to arid in nature (Western Regional Climate Center, 2011). These conditions lend little surface moisture to the soil, as only about 2.5-5cm of precipitation falls most months of the year (July- February) at the San Manuel station (Western Regional Climate Center, 2011). The months of March, April, May and June typically receive less precipitation (Western Regional Climate Center, 2011).

Southwest Arizona, where the San Pedro River is located, oscillates between wet and dry cycles over a decadal time frame (Webb and Leake, 2006). According to Hanson et al. (2006), this cycle, or the Pacific Decadal Oscillation, greatly affects streamflow and groundwater variability. The Pacific Decadal Oscillation is defined as long-term pattern in which warm or cool water will persist in the waters adjacent to the coast of Alaska (Hanson et al., 2006). This cycle is significant, as a positive change in the Pacific Decadal Oscillation index can alter the path of the jet stream, ultimately thrusting storms into Southeastern Arizona for a period of years and causing a wet period, which ultimately influences hydrological conditions on the San Pedro River (Hanson et al., 2006).

g. Settlement and agricultural history of the San Pedro River

Along the San Pedro River, there is an extensive agricultural history that spans several centuries. Arias (2000) reported that Europeans first appeared on the San Pedro River in 1538, during the Coronado Expedition from 1540-1542. Following Spaniard arrival, cattle were brought into the region. For the last 300 years, livestock grazing has been prevalent on the San Pedro River (Allen, 1989; Krueper, 1996; Krueper et al., 2003). However, around 1848, further disturbance began to affect the region (Arias, 2000; Krueper et al., 2003). People dispersed westward in response to the California gold rush, and more cattle were brought into the area for grazing. Western expansion led to settlement of lands adjacent to the river (Arias, 2000; Krueper et al., 2003). In the late 19th century, more than one million cattle were estimated to graze in Southeastern Arizona (Dobyns, 1981; Bahre, 1991; Ohmart, 1996; Krueper et al., 2003).

The San Pedro River has undergone dramatic change since European arrival and settlement. This is because before European arrival, beaver impoundments, perennial grasslands, and cienegas (marshlands) were found on the San Pedro River and were documented by those who traveled through the area around the 1850s (Arias, 2000). These descriptions of the San Pedro River indicate an ecosystem different from the one seen today, which was created by arroyo down-cutting and removal of beavers by trappers following settlement (Arias, 2000; Krueper et al., 2003). The terraces of the San Pedro River are now hydrologically different from their former state because arroyo down-cutting changed the river hydrology, ultimately causing vegetation change to take place (Green et al., 2009).

Following arroyo down-cutting, the marshlands disappeared and ecological succession took place on the former floodplain (newly formed river terraces) (Arias, 2000). In turn, *Prosopis velutina* stands, or mesquite bosques, developed on terraces adjacent to the river (Webb and Leake, 2006). Vegetation is diverse on undisturbed lands in the San Pedro River corridor, and mesquite bosques comprise approximately 60% of the 7,600 ha of vegetation in the basin (Stromberg, 1993). Mesquite bosques are important habitat because they are a biologically diverse (Stromberg et al., 1993). Woody vegetation, particularly mesquite bosque, is endemic to the area and supports wildlife on the San Pedro River. The remnant vegetation of formerly widespread mesquite bosque is important today as it represents the native terrace vegetation.

As settlement began in the 19th century on the San Pedro River, agriculture became commonplace. Native terrace vegetation was cleared, and hay, fruit, and vegetable production increased through the 1870s as more people began to populate the area (Tellman and Huckleberry, 2009). Large areas of sacaton grassland near the river were converted to agriculture in the mid-1900s (Tellman and Huckleberry, 2009). Subsequently, lumber production, cattle grazing, and multiple land uses occurred on the San Pedro River (Tellman and Huckleberry, 2009). More recently, production has declined, and agricultural abandonment has occurred (Tellman and Huckleberry, 2009).

In recent decades, there has been an increasing focus on conservation on the San Pedro River basin. Conservation focus has been on the river, but most purchases have included terrace lands. Thus, managers are faced with an opportunity to restore native ecosystems to the former agricultural fields. In recent decades The Nature Conservancy (TNC) has acquired abandoned farmlands on the San Pedro River (Tellman and Huckleberry, 2009). Land managers, including those at TNC, have engaged in restoration efforts on the San Pedro River. TNC established the Bingham Cienega Natural Preserve as one restoration project (Fonseca, 1998). Others include Three Links Farm, H&E Farm, and the San Pedro River Preserve, where TNC monitors hydrologic conditions and documents trends in vegetation (Haney, 2005). Furthermore, TNC has used replanting methods on their San

Pedro River fields in attempts to jump-start restoration (Tellman and Huckleberry, 2009). It is suspected that a history of agricultural land use has caused the abandoned fields to resist vegetation recovery following abandonment, as The Nature Conservancy efforts have been unsuccessful in restoring some properties on the San Pedro River.

h. Research intent and statement of the problem

The purpose of this research was to investigate arid restoration factors and interactions. Specifically, the intent was to identify the factors limiting restoration success and vegetation recovery of abandoned agricultural fields on terraces of the San Pedro River. Predictor variables were examined, including the history of management of old field sites, site condition information such as climate, soils and hydrology, and seed availability to identify which factors most influence the vegetation characteristics of old fields. To do this, a GIS-based site suitability analysis was developed using readily available data layers to identify abandoned agricultural fields on San Pedro River terraces. Terrace land uses were assessed using GIS, aerial photography, and land use shape files. Then, the site-suitability analysis was used to choose sampling sites for the field-based component of the project.

Next, field work was performed on the lower San Pedro River by recording woody species richness, density, basal area, and herbaceous cover in study plots in selected abandoned fields. Factors were examined that were likely influencing vegetation conditions. This was done by analyzing vegetation and soil characteristics such as soil pH, soil electrical conductivity, and soil texture. Also, land management information was analyzed, such as number of years each field was farmed, years since field abandonment, and whether post-restoration treatments were used, such as planting and/or seeding, irrigation, grazing, and mowing. GIS information was analyzed, such as field area, distance to the San Pedro River, distance to terrace vegetation, and distance to upland vegetation. These analyses were important to determine which factors were limiting vegetation growth on the San Pedro River terraces. Finally, two regression models, using woody basal area and woody stem density as response variables, were developed. These models helped determine how predictive variables like the management history, soils, field, and GIS variables might affect restoration outcomes.

CHAPTER II

METHODS

a. Study area

The San Pedro River is located in the Chihuahuan and Sonoran desert regions in Arizona and Mexico, originating in Sonora, Mexico, and flowing northward into the United States (Katz et al., 2009b). The San Pedro River flows through four southeastern Arizona counties, ending at the Gila River confluence in Winkelman, Arizona (Figure 1). The study area is the lower San Pedro River, which stretches from the narrows in Benson, Arizona to the Gila River confluence at Winkelman, Arizona. The mean annual temperature is 18.3 °C, and the mean annual precipitation is 34.5 cm at the San Manuel, Arizona climate station, centrally located on the lower San Pedro River (Western Regional Climate Center, 2011). The region is of a semi-arid to arid climate and is affected by the North American monsoon. At the San Manuel, AZ climate station, approximately 50 percent of yearly average rainfall occurs during the summer months of July, August, and September, following a dry spring season when less than 10 percent of average yearly precipitation falls in April, May, and June (Western Regional Climate Center, 2011).

The parent materials of the areas adjacent to the river floodplain are from the Holocene and are a heterogeneous mixture of materials originating from the headwater

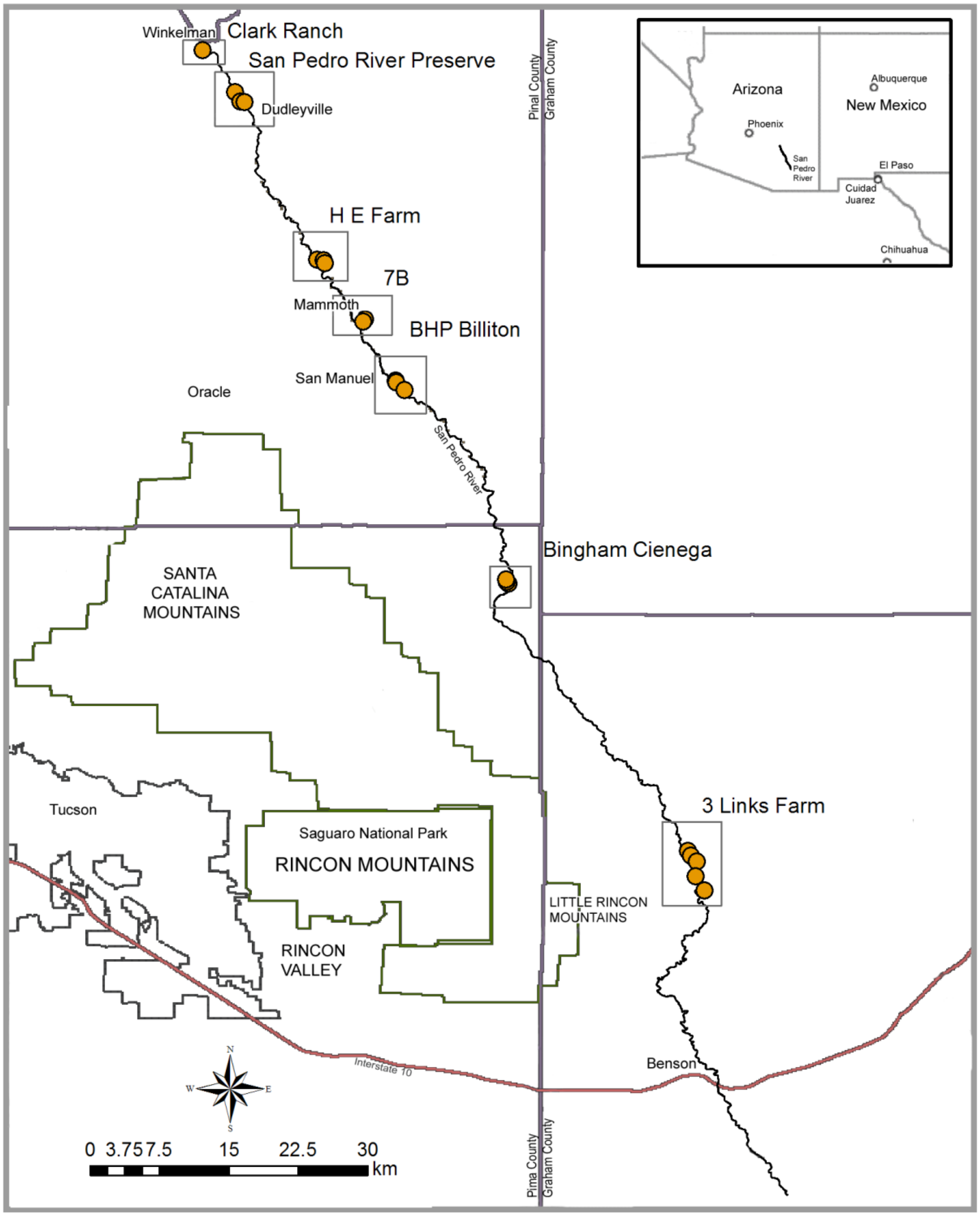

Figure 1. Study area map of the lower San Pedro River, Arizona, USA. Twenty abandoned agricultural fields, located within seven sites, were sampled in total: Clark Ranch (1 field), San Pedro River Preserve (3 fields), H & E Farm (3 fields), 7B Ranch (2 fields), BHP Billiton (3 fields), Bingham Cienega (3 fields), and Three Links Farm (5 fields).

canyons (Green et al., 2009). Present day soils are diverse and are of the entisol and aridisol soil orders (USDA-NRCS, 2011c). The USDA-NRCS defines southeastern Arizona, including the land adjacent to the San Pedro River, as having an aridic soil moisture regime (USDA-NRCS, 2011b). An aridic soil moisture regime means that soils are dry more than half of the year and are not frozen or moist for more than 90 days in a row (Buol et al., 2003). Buol et al. (2003) defined the aridic regime as an area where crop growth is considered difficult without irrigation efforts.

The San Pedro River is an important riparian ecosystem in Arizona. Although it occupies less than 1% of state land, the San Pedro River supports high biodiversity of plant and animal species, and is an ecologically important part of the desert landscape (Kreuper et al., 2003). It is also ecologically valuable in that it is the only river in the southwestern United States to remain undammed (Kreuper et al., 2003). However, the San Pedro River contains both perennial and non-perennial reaches, due to natural hydrogeologic factors as well as to water management. In the past several decades groundwater pumping has led to a decrease in ground and surface water in some reaches, which has contributed to spatially intermittent water flow (Katz et al., 2009b).

This project examines abandoned agricultural fields located on the river terraces of the San Pedro River. A terrace can be defined as a flat surface and former river floodplain that is now located above a river channel (Webb and Leake, 2006). Terraces are created by downward channel incision and erosion, and through streamflow processes such as channel widening and meandering (Webb and Leake, 2006). The terraces on the San Pedro River are adjacent to the modern floodplain (riparian zone) and are higher above the active channel. These terraces were formed during a period of arroyo downcutting believed to have been induced by frequent flooding during the 1880s-1940s, which was compounded by the human land uses of livestock grazing, and beaver trapping in the late 19th century (Webb and Leake, 2006). The causes of arroyo downcutting are debated in the literature, as Dobyns (1981) also cites a combination of factors contributing to downcutting, such as desertification, caused by livestock grazing in the region. Additionally, Waters and Ravesloot (2001) cite human impacts in the Gila River drainage basin, which includes the San Pedro River, during the late 1800s. They also document arroyo downcutting occurrences as early as 1020. This is apparent when Bull (1997) argues that arroyo downcutting would occur whether or not human impacts were present, because discontinuous streams in semi-arid environments are inherently unstable. However, once arroyo downcutting took place in the late 1800s on the San Pedro River, it caused the ground water table drop further below the terrace surfaces due to the channel itself lowering (Webb and Leake, 2006).

Native terrace vegetation is comprised largely of *Prosopis velutina* (velvet mesquite) stands, interspersed with vines, shrubs, and herbaceous vegetation (Stromberg, 1993). *Prosopis velutina*, which actively grows on the San Pedro River terraces, tends to grow where ground water is within 15 m of the surface (Havard, 1884; Cannon, 1913; Stromberg et al., 1993). Thus, it is believed that San Pedro River terraces may have somewhat shallow depth to groundwater (within 15 m of the surface). In addition to *P. velutina*, native plant species in the study area include *Baccharis sarothroides* (desertbroom), *Larrea tridentata* (creosote bush), *Acacia constricta* (whitethorn acacia), *Gutierrezia microcephala* (threadleaf snakeweed), *and Isocoma tenuisecta* (burrowweed) (Cox et al., 1993; USDA-NRCS, 2011a). In contrast, *Populus fremontii* (Fremont cottonwood) and *Salix gooddingii* (Goodding willow) occur in the riparian zone itself, on the modern day floodplain.

b. Site-suitability analysis

Site-suitability analysis was used to characterize the land cover on the San Pedro River terraces from the Benson narrows to the Gila River confluence and to identify potential sites for fieldwork. The goals for the GIS analysis were: (1) Develop and test a method for identifying old fields on lower San Pedro River terraces that were suitable for restoration, using commonly available ecological and land cover criteria, and (2) Characterize the amount of terrace and the amount of terrace occupied by old fields on the lower San Pedro River. This was completed for each output layer.

Analysis was first conducted to create a binary suitability layer and a vegetation layer. This layer was a previously hand-digitized vegetation shapefile of the lower San Pedro River, hand-digitized using 2003 1m orthophotos and prior field knowledge by M. Tluczek at Arizona State University (M. Tluczek, 2010, e-mail message to author). Information in this shapefile was extracted and reclassified to make the suitability layer "MTFields." Then a layer that was created from public, commonly available land cover data, which was named "Fields." Both layers were then compared to 2007 aerial photography for accuracy. The focus was to determine whether an *a priori* analysis using data that would be free and easily obtainable to the general public would yield similar results to the higher resolution dataset "MTFields." In this way, land managers could use this data to create an analysis of potential suitable sites for restoration on the San Pedro River.

For goal (1), specific criteria used to create the binary GIS site-suitabilty layers were: (a) the river, floodplain, and surrounding upland area could not be included in the analysis. Only terraces were suitable restoration sites, since this is where agricultural legacies originated, (b) terrace sites must have had one of the following land uses: barren land, hay/pasture, no to low development, or agriculture, and (c) field sites could not include riparian vegetation, or be located in the channel or floodplain.

Orthophotos of the study area (year 2007), created by the National Agriculture Imagery Program (NAIP), and natural vegetation shape-files at 500 m resolution, digitized from an analog map of Brown and Lowe's (2004) "Biotic Communities of the Southwest," were acquired from the Arizona Land Resource Information System (ALRIS). Terrace vegetation and land cover shape-files at 1m resolution were acquired from Arizona State University, School of Life Sciences. A National Land Cover Data (NLCD) layer at 30 m resolution, created from Landsat Imagery by the Multi-resolution Land Characteristics Consortium National Land Cover Database, was also obtained for use in this analysis (Homer et al., 2004). A Master Input Data List outlining all files used and their sources is located in Appendix A.

The first step in the site suitability analysis was to separate the terrace area from other non-terrace features in order to identify the target area for the study. Acquired orthophotos and the shape files were imported into ArcMap v9.3 (ESRI, 2008). All data were converted to the NAD_1983_UTM_Zone_12N georeferencing system for congruency and accuracy. This was accomplished by importing the orthophotos' georeferencing system to all other files using ArcToolbox. All shape files acquired for this analysis were converted to a spatial resolution of 30 meters in raster format. Next, the georeferenced shape files of the river floodplain and boundary created by M. Tluczek at Arizona State University were reclassified into one binary layer. The river boundary raster, which included the terraces and floodplain of the river, was reclassified as a 1 to denote that this was an area of interest. The floodplain raster (which was smaller than the river boundary and only included the floodplain) was classified as a 0 to denote that this feature was not of interest. The river boundary raster and the floodplain raster were then intersected into one layer. That is, the layer denoted as 1 was multiplied with the layer denoted as 0 in raster calculator. Areas labeled as 1 (terraces) were left in the newly formed layer, while areas labeled as 0 were removed through the intersection process. This action created a “terraceonly” layer, which effectively isolated the terraces from floodplains and other land features adjacent to the San Pedro River.

The next step in the site suitability analysis was to identify natural vegetation through the use of a layer that showed vegetation types in the study area. This layer isolated vegetation on terraces. To meet this goal, a natural vegetation shapefile from ALRIS, digitized from Brown and Lowe (2004), was obtained. This layer was reclassified into a binary layer, where 0 denoted vegetation not present on terraces, and 1 denoted vegetation of interest, which was Chihuahuan and Sonoran desert scrub (Table 1). This action effectively excluded vegetation not physically present on the terraces and located outside of the terrace land area, creating the “natveg” layer. Included in the analysis was an NLCD raster layer, created from Landsat imagery, which was also reclassified into a binary layer. The layer was reclassified into relevant and non-relevant land cover: Barren Land, Shrub/Scrub, Developed—open space, Developed—Low Intensity, and Croplands were classified as a 1, and all other land cover types were classified as a 0 (Table 2). This action excluded extraneous vegetation cover, outside of the terraces, as well as unsuitable land cover. Including Developed—open space, Developed—low intensity, Barren Land, and Cropland allowed for possible farm areas to be included in the analysis. Vegetation types were chosen because they were similar to vegetation found on San Pedro River terraces. Reclassification into unsuitable and suitable vegetation created the “landcover” layer. Finally, all layers were intersected through use of multiplication in raster calculator. The following equation was used in the raster calculator program: “Fields=terraceonly*natveg*landcover.”

Table 1. Vegetation cover types present in the ALRIS (Arizona Land Resource Information System) natural vegetation cover shape file, which was digitized from Brown and Lowe’s (2004) “Biotic Communities of the Southwest.”

Natural Vegetation Type	**Inclusion in Analysis**
Interior Chaparral	No
Semidesert Grassland	No
Madrean Evergreen Woodland	No
Petran Montane Conifer Forest	No
Great Basin Conifer Woodland	No
Plains and Great Basin Grassland	No
Chihuahuan Desert Scrub	**Yes**
Sonoran Desert Scrub	**Yes**

Table 2. Vegetation cover types present in the NLCD (National Land Cover Database) land cover shape file.

NLCD Cover Type	**Inclusion in Analysis**
Open Water	No
Perennial Snow and Ice	No
Developed, Open Space	**Yes**
Developed, Low Intensity	**Yes**
Developed, Medium Intensity	No
Developed, High Intensity	No
Barren Land	**Yes**
Deciduous Forest	No
Evergreen Forest	No
Mixed Forest	No
Shrub/Scrub	**Yes**
Herbaceous	No
Hay/Pasture	**Yes**
Cropland	**Yes**
Woody Wetlands	No
Emergent Herbaceous Wetlands	No

Next, a comparison of this suitability analysis with a land cover shapefile of the lower San Pedro River, obtained from colleagues at Arizona State University (M. Tluczek, 2010, unpublished data in e-mail message to author), was performed (Appendix A). This land cover shape file included 7 cover types, 3 geomorphic classifications nested within the cover types, and 7 percentage cover classifications nested within each of the 3 geomorphic types. This equaled a total of 147 categories, serving as the most detailed record available of lower San Pedro River vegetation available for this project (Table 3). To analyze the different cover types in the shapefile, the shapefile was converted to raster format. Next, a layer representing farmland, or lands classified as agricultural in nature by M. Tluczek, were extracted and reclassified. In this layer, any area that encompassed 100% farmland was classified as a 1. If the area included less than 100% farmland, it was reclassified as a 0. This reclassified layer was named "farm." Additionally, a layer representing bare ground was extracted from the file and reclassified into a layer representing a bare ground cover type. Any terrace area representing 100% bare ground in the file was classified as a 1, and any area representing bare ground coverage of less than 100% was classified as a 0. Since most abandoned fields are not well-vegetated, this action was done to exclude land areas that could have been active fields or other land areas not abandoned. This new layer was named "bareground." Other categories were not chosen because they were not representative of what abandoned field land cover might include, or the cover was located on a channel or floodplain area, rather than the terrace. These layers were intersected in raster calculator using the equation: "MTfields=farm*bareground *terraceonly."

Table 3. Vegetation cover types present in the shapefile provided by Arizona State University (M. Tluczek, 2010, unpublished data in e-mail message to author) vegetation and land cover shape file. Those used in the site suitability analysis are highlighted. Note that each cover type within each geomorphic class was subdivided into 7 different percent cover classes (0%, 5%, 20%, 40%, 60%, 80%, and 100%).

Vegetation Cover Type	**Classification**	**% Cover Class within Geomorphic Class Included in Analysis**	**Inclusion of layer in Analysis**
Tall Trees	Channel	N/A	No
	Terrace	N/A	No
	Floodplain	N/A	No
Woody	Channel	N/A	No
	Terrace	N/A	No
	Floodplain	N/A	No
Herbaceous	Channel	N/A	No
	Terrace	N/A	No
	Floodplain	N/A	No
Bare Ground	Channel	N/A	No
Bare Ground	**Terrace**	**100**	**Yes**
	Floodplain	N/A	No
Anthropogenic—Farm	Channel	N/A	No
Anthropogenic—Farm	**Terrace**	**100**	**Yes**
	Floodplain	N/A	No
Anthropogenic—Other	Channel	N/A	No
	Terrace	N/A	No
	Floodplain	N/A	No
Dead Wood	Channel	N/A	No
	Terrace	N/A	No
	Floodplain	N/A	No

Finally, the two methods were compared to the orthophotos to compare the results from the “Fields” site-suitability analysis to the results obtained from M. Tluczek’s method of digitizing aerial photography (“MTFields”). Hectares of terrace land found suitable and unsuitable for restoration were recorded. Total terrace area in each layer was also recorded. Additionally, random points were generated for an accuracy assessment within the “Fields” and “MTfields” layers. This was performed using the Create Random Points feature in ArcToolbox. This command generated many points, and 200 points, or 50 points per class, which equaled 100 points per layer, were randomly chosen for the accuracy assessment. Each point was visually inspected to determine whether the classification was correct. The “MTFields” vegetation layer and the “Fields” layer were verified against the orthophotos for accuracy. The “Fields” layer was compared to both the “MTFields” layer and the orthophotos. It was necessary to use the “MTFields” layer for comparison, because the vegetation differences and types, and the land uses could not be fully determined by the orthophotos alone. Each point was recorded as correct or incorrect in a Microsoft Excel spreadsheet. Additionally, points were entered into an error matrix to determine errors of omission (Producer’s accuracy), meaning an error involving the probability of suitable or unsuitable lands being correctly classified (Jensen, 2005). Errors of commission (User’s accuracy) were also calculated, which can be defined as the accuracy at which what is classified as suitable or unsuitable represents that category (Jensen, 2005). Additionally, the error matrix reported the overall accuracy rate of the binary classification.

c. Field site selection

Twenty study sites, abandoned agricultural fields on San Pedro River terraces, were chosen for field work using a combination of the GIS site-suitability analysis (described above), and convenience sampling of known Nature Conservancy-owned fields. First, fields were identified remotely by hand-selecting large tracts of suitable lands in the binary “Fields” layer from the suitability analysis. Fields were then checked for accuracy and location using newest available orthophotos (year 2007) and the “MTFields” GIS vegetation layer.

Local land managers were contacted to inquire about potential study sites, in order to determine whether preliminary GIS-selected field sites were suitable for this study. Land managers were asked about land histories, specifically whether field sites were abandoned agricultural fields. A site must have been on an abandoned agricultural field to be included in the study. Next, preliminary management questions were asked about restoration techniques. In this study, fields with varying post-agricultural managements, ranging from no restoration to active restoration could be included. This is because fields were sought in which natural recovery was either being encouraged by restoration treatments, or was being left to recover without treatment in order to investigate the question of whether restoration treatments were encouraging vegetation recovery.

Next, field sites were selected based on their variability. The range of histories and restoration treatments used or not used were intended to be factors in this study, so choosing a variety of field sites with differences was preferable. Finally, final permissions were obtained from field managers to conduct fieldwork at each site and sites were selected using our criteria, combined with input from land managers of each field site. Of the many field sites available from the GIS model, twenty field sites that coincided with land manager approval were selected to allow for a representative sample of the old field terraces.

All sites were located on lower San Pedro river terraces and were managed by either The Nature Conservancy, BHP Billiton, or private landowners (Figure 1). Twenty fields were sampled in total. These fields were located within seven larger sites along the river. The most northward site was in Dudleyville (Clark Ranch), and from there, sites were located southward, with the most southward site located fifteen miles north of Benson (Three Links Farm) (Figure 1). Fields sampled included Clark Ranch (1 field), San Pedro River Preserve

(3 fields), H & E Farm (3 fields), 7B Ranch (2 fields), BHP Billiton (3 fields), Bingham Cienega (3 fields), and Three Links Farm (5 fields) (Figure 1). Field site maps are provided in Appendix C.

d. Field vegetation sampling

Vegetation data was collected in three randomly located 10 m^2 plots in each field during May-June, 2010 (Figure 2). Plots were not placed within 10 m of the edge of the field to ensure that edge effects were not captured during data collection. GPS plot coordinates were recorded with a hand-held Garmin eTrex Legend GPS unit to mark exact latitude-longitude locations in the southwest corner of each plot (Appendix B). Additionally, elevation was recorded in the southwest corner of each plot with the GPS unit. To quantify vegetation structure, all woody species present in the plots were recorded and identified (Kearney and Peebles, 1960). Woody species richness, defined as the number of live species present in each plot, was recorded. Woody stem density, or the number of stems present in each plot, was recorded by species. Stem diameter at basal height of each woody species was recorded in three classes: <1 cm, 1-3 cm, and >3 cm. Total herbaceous cover was recorded in seven categories: <1%, 1-5%, 6-25%, 26-50%, 51-75%, 76-95%, and >95%, based on visual estimation of herbaceous cover in the plot.

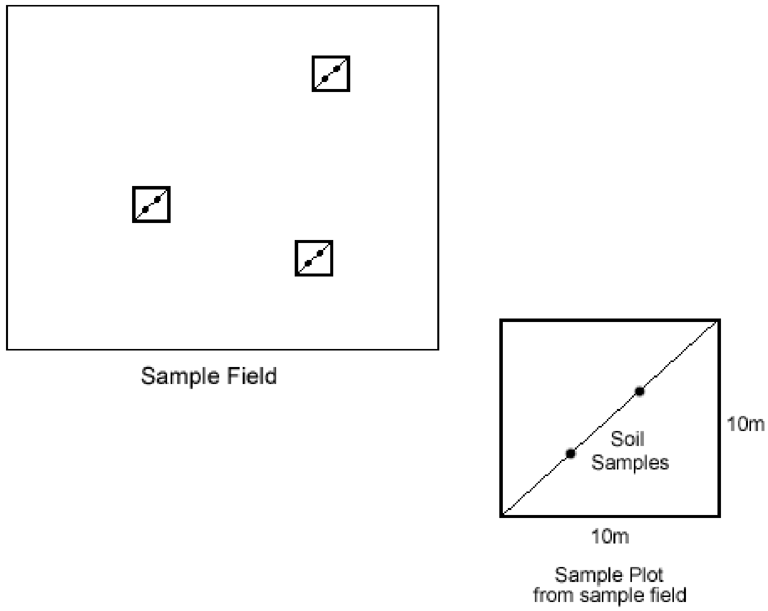

Figure 2. Field sampling method. Close-up of a sample plot shows that each plot was 10 x 10 m in size. Also, transect was always run from the southwest corner to the northeast corner of the plot, and soil samples were taken equidistant from each other in the plot, along the transect.

e. Soil sampling

Two soil surface samples, 10 cm deep x 2 cm diameter, were removed by soil auger along a line running diagonally from the southwest to northeast corner of each 10 m^2 plot. The two soil samples were spaced evenly along each transect (Figure 2). This process assured that samples represented any varied soil conditions found on each plot (Harms and Hiebert, 2006; Bay and Sher, 2008). Surface vegetation and roots were removed and samples were collected and stored in Ziploc bags labeled by plot and field. Samples were then dried in an oven for 48 hours, and combined in equal portions (200 g from each transect point sample), to form a homogenous mixture for each plot.

Composite plot soil samples were analyzed for pH and texture at the plot level in the Sedimentology Lab at the University of North Carolina, Wilmington. Soil pH was determined according to standards outlined in the Soil Survey Laboratory Methods Manual (USDA-NRCS, 2004) in a 1:1 mixture of soil to distilled water using a Fisher Automated pH meter. Texture was analyzed by soil particle size analysis through the use of an electronic particle size counter (Coulter Counter) which is a more efficient, though comparable method of soil texture analysis to traditional pipette methods (Pennington and Lewis, 1979). The Coulter Counter yielded exact percentages of sand silt, and clay for each plot. Electrical conductivity, a proxy for soil salinity, was analyzed by AGVISE commercial laboratory using the electrical conductivity of a saturated soil paste. All plot level measurements of soil texture, pH, and electrical conductivity were then averaged at the field level for data analysis.

f. Field history and management data

In order to determine the unique history of management and restoration efforts at each site, local land managers were contacted for historical information. In particular, Barbara Clark, a field manager at The Nature Conservancy of Arizona (TNC Arizona) provided information about Bingham Cienega and Three Links Farm sites. Molly Hanson (TNC Arizona) provided information about San Pedro River Preserve and Clark Ranch fields and Celeste Andresen (TNC Arizona) provided information about 7B Ranch field sites. Additionally, Gerald Brunskill of BHP Billiton provided historical information of old fields owned by the mining company. All land managers were interviewed in person in May-June, 2010. Land managers were contacted again for any additional unknown information by telephone/email in October 2010. In the interviews, several questions were posed in numerical (year) and categorical (yes/no) formats. Land managers were asked what years the fields were farmed, what year the fields were abandoned, and whether the following post-abandonment restoration treatments were or were not implemented on fields: planting and/or seeding, irrigation, grazing, or mowing.

g. Field environmental data

Additional field characteristics were determined through the use of ArcGIS v9.3 (ESRI, 2008). Using the orthophotos of the study area, the size of each field was calculated and distance to the San Pedro River, distance to upland vegetation, and distance to terrace vegetation were calculated in order to obtain characteristics of each field for input into a regression model. Field boundaries were hand-drawn in ArcMap using the sketch tool within the Editor Toolbar. After field boundary lines were drawn, buffers were created using the buffer tool within the Editor Toolbar. Buffers were calculated in 25 m increments, and were based from the perimeter of each field (boundary lines). Using the buffer data, distances to various cover types were calculated to the nearest 25 m. Additionally, field area was calculated in hectares by adding a field in the layers attribute table and using the field calculator in ArcMap.

h. Data analysis

All data analysis was conducted using SAS 9.3 (SAS Institute Incorporated, 2008). In SAS, multiple linear regression analysis was performed using the PROC STEPWISE command. This analysis, conducted at the 95% confidence interval ($\alpha = 0.05$), was used to determine the effects of multiple predictor variables on woody stem density, and woody basal area, the response variables. Plot level data were averaged by field prior to regression analysis. Field and environmental data such as soil charcteristics (pH, electrical conductivity, and sand silt and clay texture), field history/management (years farmed, years since abandonment, planting and/or seeding, irrigation, grazing, and mowing), environmental GIS data (field area, distance to river, distance to terrace vegetation, distance to upland vegetation), and GPS elevation were used as predictor variables in the regression analysis.

Two separate models were created to assess the effects of predictor variables on vegetation metrics. One model tested predictor variables for woody basal area, and the other model tested predictor variables for woody stem density. The Shapiro-Wilk test was used to test all data for normality. Since woody basal area and stem density were not normally distributed, they were square root-transformed to meet the assumptions of a normal distribution. All analyses were conducted on the transformed vegetation (woody stem density and woody basal area) data. Variables were allowed to enter the STEPWISE model at any threshold α level to allow for all combinations of variables to be tested. However, variables were only included in the final analysis if they met an $\alpha = 0.05$ level of significance after entering the model.

Additionally, herbaceous cover values at the field level were investigated for possible relationships with the response variables (woody stem density and basal area). Using the PROC REG command, a simple linear regression was performed at the 95% confidence interval ($\alpha = 0.05$) to determine if there was a relationship between herbaceous growth (predictor variable) and basal area (response variable). A second simple linear regression was performed to test for any relationship between herbaceous growth and woody stem density.

The PROC GLM command was used to perform a one-way Analysis of Variance (ANOVA) to test for the effects of management treatments on vegetation structure. Specifically, the effect of each post-abandonment restoration treatment (i.e., planting and/or seeding, irrigation, grazing, or mowing), on woody basal area and woody stem density was assessed. One additional ANOVA assessing the treatment effect of planting/seeding on herbaceous cover was also performed. All ANOVAs were tested at the 95% confidence interval ($\alpha = 0.05$).

CHAPTER III

RESULTS

a. Site-suitability analysis

In the site suitability analysis, two output layers were created, “Fields,” and “MTFields.” On the lower San Pedro River, the “Fields” layer classified 11038 ha as total terrace area (Table 4). “Fields” also found that 2048 ha (19%) of terrace lands were suitable for restoration, and 9577 ha (81%) of river terraces were likely unsuitable for restoration (Table 4). Similarly, “MTFields” classified 10934 ha as total terrace area, which was 104 ha less land area classified as terrace than in the “Fields” layer (Table 4). “MTFields” layer also found that 1461 ha (13%) of terrace lands were suitable for restoration purposes, while 8886 ha (87%) of river terraces were unsuitable for a restoration (Table 4).

Table 4. Values of suitable and unsuitable land on the river terraces on the lower San Pedro River, Arizona. The “Fields” analysis yielded similar results to the “MTFields” analysis.

Layer	Suitable (ha)	% Suitable	Unsuitable (ha)	% Unsuitable	Total area
Fields	1461	13%	9577	87%	11038
MTFields	2048	19%	8886	81%	10934

Additionally, the GIS site-suitability accuracy assessment yielded a high Producer's accuracy rate (low omission error) for the "Fields" layer. Of the 100 random points, 50 points per class comparison of "Fields" to the orthophotos, 82 points were confirmed to be accurate, yielding an 82% overall accuracy rate (Table 5). In the "Fields" layer class that determined land areas unsuitable for restoration, 33 of 50 points were accurate, yielding a 66% Producer's accuracy rate, or 34% omission error (Table 5). The analysis also yielded a 74% User's accuracy rate, or 26% commission error (Table 5). In the category of land area suitable for restoration, 49 of 50 points were accurate, yielding a 98% Producer's accuracy rate, or 2% omission error (Table 5). Additionally, The analysis also yielded a 97% User's accuracy rate, or 3% commission error (Table 5). Essentially, the site suitability analysis was less discriminating in determining suitable land for restoration than the "MTFields" layer, which yielded a perfect (100%) overall accuracy rate (Table 6). "MTFields" also showed perfect Producer's and User's accuracy rates, and 0% omission and commission errors (Table 6). Finally, the accuracy assessment of the "Fields" layer also yielded similar results when compared to the 2007 orthophotos (Figure 3). Overall, results point to the model's ability to determine where unknown abandoned fields might be located on the lower San Pedro River.

Table 5. Site-suitability error matrix for the “Fields” layer when compared to the 2007 orthophotos. Error matrix shows accuracy assessment results for “Fields” by binary class. Note the high Producer’s accuracy rate for the suitable class, and lower Producer’s accuracy rate for the unsuitable field class.

	Suitable	**Unsuitable**	**Row Total**
Suitable	**49**	17	66
Unsuitable	1	**33**	34
Column Total	50	50	**100**

Overall Accuracy = 82/100 = 82%

Producer's Accuracy (omission error)		**User's Accuracy (commission error)**	
Suitable = 49/50 = 98%	2% omission error	Suitable = 49/66 = 74%	26% commission error
Unsuitable = 33/50 = 66%	34% omission error	Unsuitable = 33/34 = 97%	3% commission error

Table 6. Site-suitability error matrix for the “MTFields” layer when compared to the 2007 orthophotos. Error matrix shows accuracy assessment results for “MTFields” by binary class. Note the 100% Producer’s and User’s Accuracy rates for all categories.

	Suitable	**Unsuitable**	**Row Total**
Suitable	**50**	0	50
Unsuitable	0	**50**	50
Column Total	50	50	**100**

Overall Accuracy = 100/100 = 100%

Producer's Accuracy (omission error)		**User's Accuracy (commission error)**	
Suitable = 50/50 = 100%	0% omission error	Suitable = 50/50 = 100%	0% commission error
Unsuitable = 50/50 = 100%	0% omission error	Unsuitable = 50/50 = 100%	0% commission error

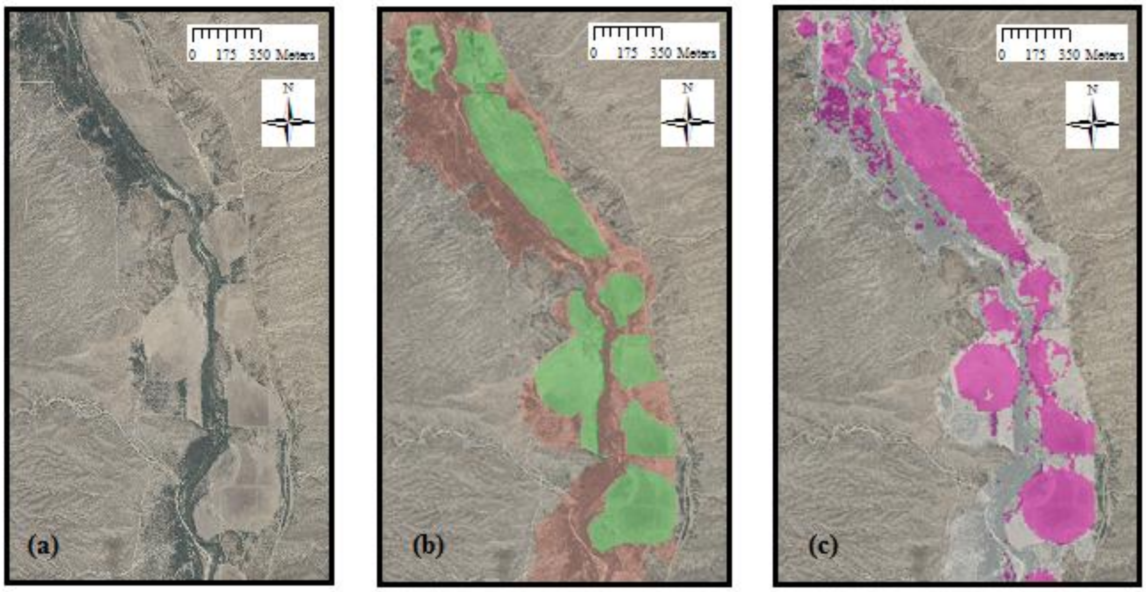

Figure 3. Fields at Three Links Farm in Cochise County, Arizona, that were identified in the site suitability analysis. Fields are clearly visible in the 2007 othrophoto (a). The “MTFields” layer (b) and the “Fields” Layer (c) show very similar results when compared to each other, as well as high accuracy compared to the orthophotos. Suitable field areas are in green on (b) and purple on (c).

b. Field characteristics

Vegetation

In total, there were seven woody species present at all field sites, indicating overall low woody species richness in the sampled abandoned fields (Table 7). Species present were all native and included *Prosopis velutina* (velvet mesquite), *Baccharis sarothroides* (desert broom) *Larrea tridentata* (creosote bush), *Acacia constricta* (whitethorn acacia), *Gutierrezia microcephala* (threadleaf snakeweed), *Isocoma tenuisecta* (burroweed), and *Atriplex polycarpa* (cattle saltbush) (Kearney and Peebles, 1960). Field sites were sparsely vegetated in most areas, and were characterized by low woody stem density and basal area. Stem density ranged from 0 to 8633.3 stems/ha (Table 7). Woody basal area ranged from 0 to 29.6 m^2/ha (Table 7). When woody vegetation was present, *P. velutina* (alive and dead) was the primary species observed. Additionally, percent herbaceous cover ranged greatly at field sites, from 11.3% at Three Links #1, to 97% at Bingham Cienega #1.

Table 7. Vegetation conditions on San Pedro River field sites.

Field Site Name	Species Present	Stem Density (stems/ha)	Basal Area (m^2/ha)	% Herbaceous Cover
Three Links #1	*P. velutina*	233.3	0.2	11.3
Three Links #2	*P. velutina*	2433.3	8.1	15.5
Three Links #3	*P. velutina*	2433.3	3.9	38.8
Three Links #4	*P. velutina*	1366.7	0.6	54.7
Three Links #5	*P. velutina, B. sarothroides, G. microcephala I. tenuisecta*	8633.3	5.1	53.8
7B Ranch #1	*P. velutina*	2933.3	18.3	46.3
7B Ranch #2	*P. velutina*	3533.3	26.0	38.8
Bingham Cienega #1	*P. velutina*	3566.7	29.6	97.0
Bingham Cienega #2	*P. velutina*, Dead *P. velutina*	300.0	0.0	69.7
Bingham Cienega #3	*P. velutina, B. sarothroides*	366.7	1.1	81.8
BHP Billiton #1	*P. velutina*	3000.0	6.9	63.0
BHP Billiton #2	*P. velutina, L. tridentata, A. constricta*	1400.0	3.9	38.0
BHP Billiton #3	*P. velutina*	2200.0	7.2	54.7
Clark Ranch	*P. velutina*	950.0	1.4	85.5
H&E #1	None	0.0	0.0	74.3
H&E #2	*P. velutina*	133.3	2.1	46.3
H&E #3	*P. velutina*	366.7	1.7	50.5
SPRP #1	*P. velutina*	33.3	0.0	81.8
SPRP #2	*P. velutina*, Dead *P. velutina, A. polycarpa*	500.0	5.6	53.8
SPRP #3	*P. velutina, B. sarothroides*	633.3	0.6	78.0

Soils

Soils at the field sites were composed primarily of silt and sand, with very little clay present (Table 8; Figure 4). Percent clay in the soil ranged from 2.1% to 6.4%, silt from 16.8% to 52.5%, and sand from 41.0% to 80.8% (Table 8). Field soils can be described as agriculturally modified entisols, as they were defined by a lack of moisture and a homogenous soil color that showed a lack of developed soil horizons (Buol et al., 2003; USDA-NRCS, 2011c). Additionally, field soil samples were characterized by an alkaline pH, and the minimum soil pH present at sites was 8.1 (Table 8). Electrical Conductivity (EC), a proxy measurement for soil salinity, was measured and total dissolved salt levels were found to be within a medium to high range at all field sites (USDA-NRCS, 2004).

Table 8. Average soil parameters by field site. Each field is an average value based on three plot values, thus n = 3.

Site Name	**pH**	**EC (mmhos/cm)**	**% Clay**	**% Silt**	**% Sand**
Three Links #1	8.1	2.2	2.4	16.8	80.8
Three Links #2	8.7	1.8	3.8	46.4	49.8
Three Links #3	8.4	1.4	3.0	32.1	64.9
Three Links #4	8.5	1.1	3.5	35.6	60.9
Three Links #5	8.4	0.8	3.0	26.9	70.1
7B Ranch #1	8.3	1.9	5.9	53.1	41.0
7B Ranch #2	8.5	1.1	6.1	37.5	56.3
Bingham Cienega #1	8.2	0.8	4.5	24.6	70.9
Bingham Cienega #2	8.1	1.8	3.2	21.0	75.8
Bingham Cienega #3	8.6	0.9	4.7	26.3	69.0
BHP Billiton #1	8.8	0.9	4.7	44.2	51.0
BHP Billiton #2	8.8	0.5	4.5	42.3	53.1
BHP Billiton #3	8.7	0.5	4.2	42.9	52.9
Clark Ranch	8.2	0.6	2.1	22.4	75.5
H&E #1	8.7	0.9	6.4	52.5	41.1
H&E #2	8.5	1.5	6.3	49.1	44.6
H&E #3	8.8	1.0	5.5	50.7	43.8
SPRP #1	8.8	0.8	2.7	27.7	69.6
SPRP #2	8.9	0.5	2.2	21.6	76.2
SPRP #3	8.6	0.6	3.9	36.1	60.0

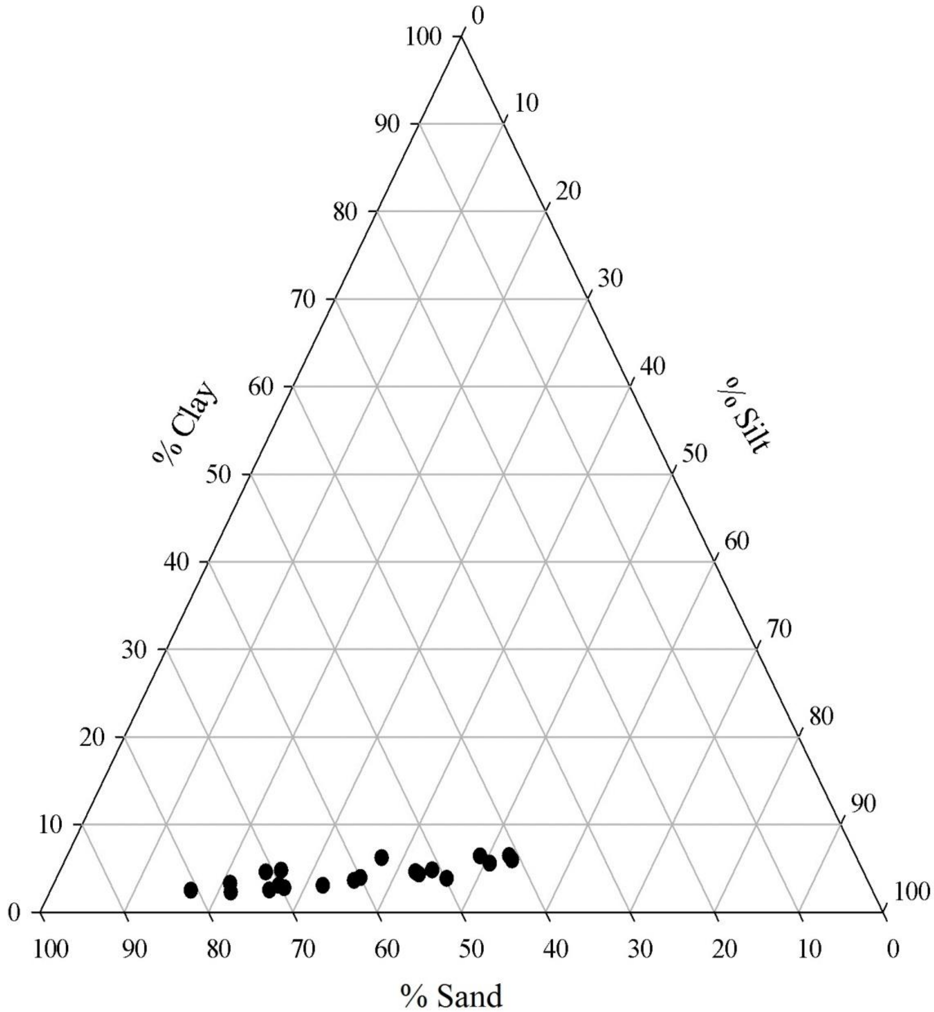

Figure 4. Textural analysis results for soil samples taken at field sites. Each point represents average soil texture in each field. Soil particles are predominantly sand and silt.

Field environmental data (GIS)

The fields varied in terms of environmental conditions. Field size (area) ranged from 1.6426 ha at Bingham Cienega #1 to 60.39 ha at Three Links #2, with a mean of 15.19 ha

(Table 9). Fields were all less than 1km distance from the San Pedro River channel, though distances ranged from 25 m away from the river (Three Links #1-2, BHP Billiton #3, and Clark Ranch) to 750 m (7B Ranch #1). Distances to terrace and upland vegetation were also different for each field site, though terrace vegetation was fairly close to fields. The distance to terrace vegetation ranged from 25 m at most fields sites (Three Links #1-#5, 7B Ranch #1-2, Bingham Cienega #1, BHP Billiton #2-3, Clark Ranch, H&E #2-3, SPRP #1-2) to 250 m at H&E #1, with a mean distance of 52.5 m. Distance to upland vegetation ranged from 50 m at several field sites (Three Links #2, Three Links #4, Clark Ranch, H&E #2-3, SPRP #2) to 450 m at SPRP #3, with a mean of 187.5 m. Distance to upland vegetation was variable, but was always less than 0.5 km from each field.

Table 9. Field parameters calculated in ArcGIS.

Field Site Name	Field Area (ha)	Distance to River (m)	Distance to Terrace Vegetation (m)	Distance to Upland Vegetation (m)
Three Links #1	59.72	100	25	175
Three Links #2	60.39	50	25	50
Three Links #3	15.42	25	25	200
Three Links #4	23.44	25	25	50
Three Links #5	44.85	50	25	200
7B Ranch #1	4.74	750	25	75
7B Ranch #2	8.38	400	25	200
Bingham Cienega #1	1.64	175	25	400
Bingham Cienega #2	3.60	275	100	200
Bingham Cienega #3	5.66	200	100	175
BHP Billiton #1	12.84	275	175	400
BHP Billiton #2	3.92	500	25	375
BHP Billiton #3	12.04	25	25	200
Clark Ranch	4.63	25	25	50
H&E #1	7.43	50	250	300
H&E #2	10.02	50	25	50
H&E #3	7.80	125	25	50
SPRP #1	6.21	225	25	100
SPRP #2	6.19	100	25	50
SPRP #3	4.84	50	50	450

Agricultural Field History and Management

Fields were all privately owned decades ago, but The Nature Conservancy now manages or owns the majority of the field sites, with the exception of three fields owned by a mining company, BHP Billiton (Table 10). All fields were abandoned between 1985 and 2002. Fields were farmed for several decades, and years farmed range between 60 and 120 years. Elevation differences existed between field sites by as much as 300 m; however, there is an elevation gradient along the river, where elevation decreases as the river flows northward. Thus, elevation differences represent longitudinal distance along the river, and not differences in terrace elevation above the river channel or groundwater surface elevation.

Most fields have undergone multiple post-abandonment restoration treatments. The exceptions to this were fields at the BHP Billiton property, which were un-treated in the post-agricultural period. Specifically, nine fields experienced post-planting and/or seeding restoration treatments (Three Links #2, Bingham Cienega #2-3, H&E #1-3, SPRP #1-3), while 11 did not (Table 10). Irrigation occurred in five fields (Three Links #3-4, Bingham Cienega #2, SPRP #2-3), while fifteen were not irrigated. Grazing was allowed at thirteen field sites (Three Links #1, Three Links #3-5, 7B Ranch #1-2, Bingham Cienega #1-3, Clark Ranch, H&E #1-3), but did not occur at the other seven sites. Mowing as a restoration treatment occurred at 10 field sites (Three Links #1-5, H&E #1-3, SPRP #1-2), but not at the other ten.

Table 10. Study sites with relevant descriptive information, including history and post-abandonment management practices.

Site Name	Agency	Elev (m)	Years Farmed	Years Since Abandonment	Plant/ Seed	Irrigation	Graze	Mow
Three Links #1	TNC	999	65	10	No	No	Yes	Yes
Three Links #2	TNC	996	60	8	Yes	No	No	Yes
Three Links #3	TNC	988	110	10	No	Yes	Yes	Yes
Three Links #4	TNC	980	110	10	No	Yes	Yes	Yes
Three Links #5	TNC	986	120	10	No	No	Yes	Yes
7B Ranch #1	TNC	742	65	25	No	No	Yes	No
7B Ranch #2	TNC	711	65	25	No	No	Yes	No
Bingham Cienega #1	TNC / private landowners	850	75	22	No	No	Yes	No
Bingham Cienega #2	TNC / private landowners	848	75	22	Yes	Yes	Yes	No
Bingham Cienega #3	TNC / private landowners	847	75	22	Yes	No	Yes	No
BHP Billiton #1	BHP	747	100	16	No	No	No	No
BHP Billiton #2	BHP	749	100	16	No	No	No	No
BHP Billiton #3	BHP	753	100	16	No	No	No	No
Clark Ranch	TNC	594	90	13	No	No	Yes	No
H&E #1	TNC	688	75	14	Yes	No	Yes	Yes
H&E #2	TNC	689	75	14	Yes	No	Yes	Yes
H&E #3	TNC	697	75	14	Yes	No	Yes	Yes
SPRP#1	TNC	615	90	13	Yes	Yes	No	Yes
SPRP #2	TNC	611	90	13	Yes	Yes	No	Yes
SPRP #3	TNC	612	90	13	Yes	No	No	No

c. Regression and Analysis of Variance models

Woody Basal Area

The best regression model included distance to terrace vegetation, soil percent clay, and planting/seeding as significant predictors of woody basal area in abandoned fields ($r^2 = 0.5765$, $p = 0.0027$, Table 11). Soil texture (clay) was the only variable in the regression model to have a positive relationship with basal area. Distance to terrace vegetation and use of planting and/or seeding treatments had a negative relationship with basal area. In three fields with high basal area (Bingham Cienega #1, and 7B Ranch #1-2), terrace vegetation is within 25 m of the fields (Figure 5).

Table 11. Multiple regression results for woody basal area as the response variable. Results for this 3 variable model are $r^2 = 0.5765$, $p = 0.0027$.

Variable	Parameter Estimate	F	P
Distance to terrace vegetation	-0.01957	8.6	0.0097
Percent clay	0.77321	7.24	0.0161
Post planting and/or seeding	-1.87038	6.28	0.0234

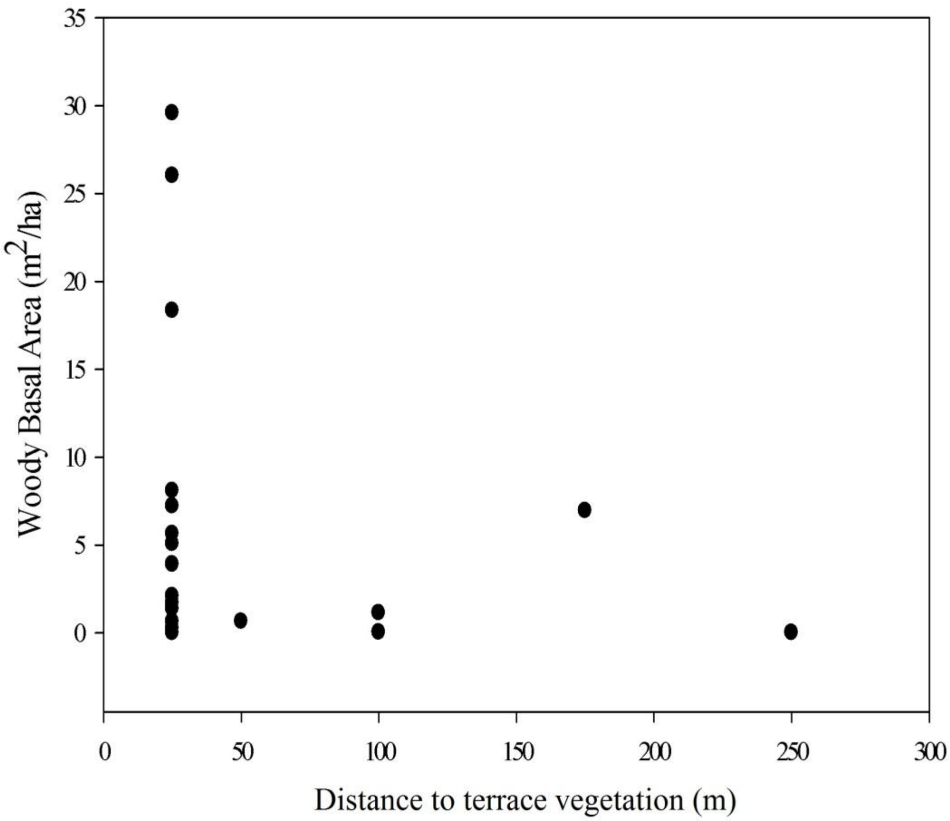

Figure 5. Distance to terrace vegetation as a predictor of woody basal area.

ANOVA indicated that post planting and/or seeding had a significant effect on woody basal area (df = 1, F-value = 5.63, p-value = 0.0289, Figure 6). Mean and SE of basal area in untreated fields was 9.4 m^2/ha ± 0.9. The mean and SE of basal area for treated fields was 2.1 m^2/ha ± 0.3. However, the treatment effect was negative; when planting and/or seeding treatments were implemented, woody basal area decreased in fields. There were no significant treatment effects of irrigation (df = 1, F-value = 2.19, p-value = 0.1561), mowing (df = 1, F-value = 3.09, p-value = 0.0959) or grazing (df = 1, F-value = 0.00, p-value = 0.9485) on basal area

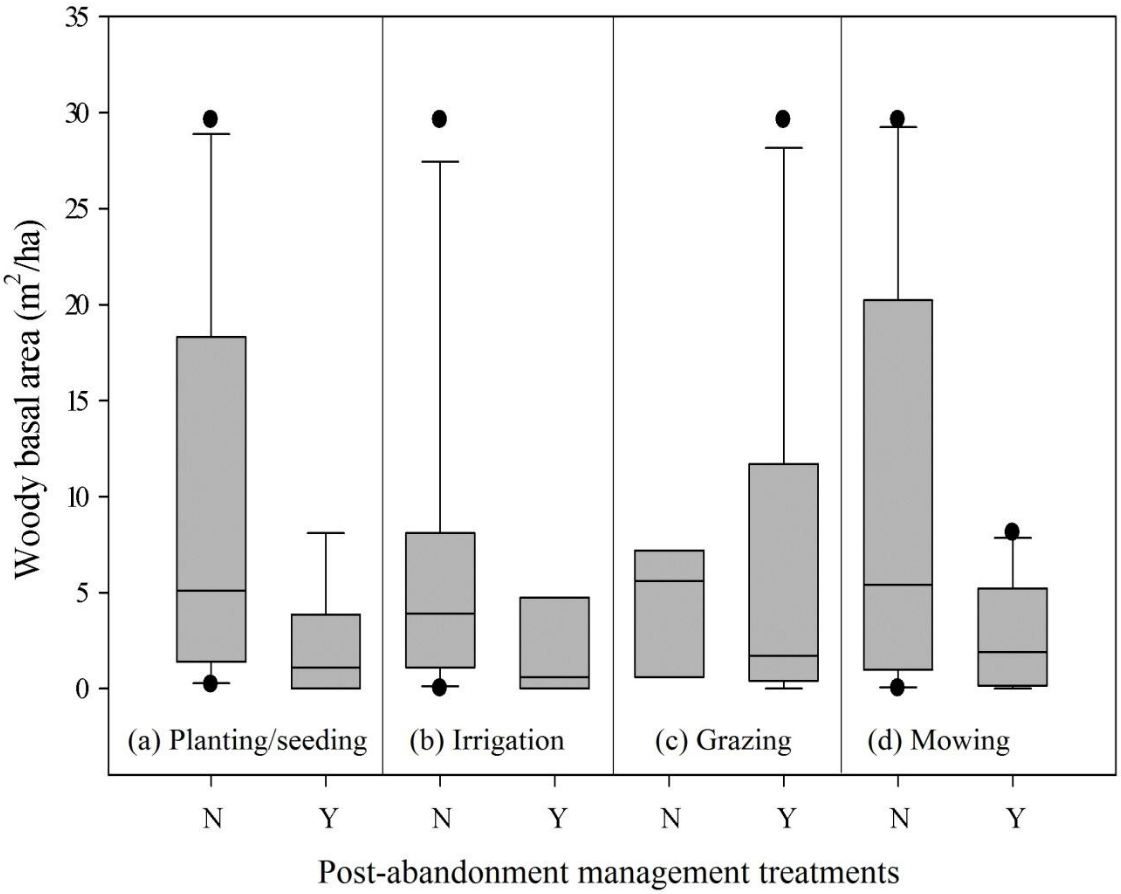

Figure 6. Woody basal area in abandoned agricultural fields as a function of restoration treatment. (a) N = not planted and/or seeded for restoration (*n* =11), Y = planted and/or seeded (*n*=9). (b) N = not irrigated for restoration (*n* =15), Y = irrigation was used (*n* = 5). (c) N = no grazing was allowed for restoration (*n* =7), Y = grazing was allowed (*n* =13). (d) N = not mowed (*n* =10), Y = mowing was performed (*n* =10).

Woody Stem Density

When management, history, soil, and environmental variables were analyzed for predictive relationships with woody stem density (response variable), there was a significant effect of field area, years farmed, and time since abandonment on woody stem density in abandoned fields ($r^2 = 0.6134$, $p = 0.0013$). These relationships were all positive, indicating that woody stem density increases with increased field size, number of years farmed, and time since abandonment (Table 12).

Table 12. Multiple regression results for woody stem density as the response variable. Results for this 3 variable model are $r^2 = 0.6134$, $p = 0.0013$.

Variable	**Parameter Estimate**	**F**	**P**
Field area	0.00001	17.15	0.0008
Years farmed	0.10761	18.36	0.0006
Time since abandonment	0.42473	16.88	0.008

Stem density ANOVA results were similar to basal area results, in that post planting and/or seeding had a significant effect on density (df = 1, F-value = 14.53, p-value = 0.0013, Figure 7). However, the treatment effect was negative and woody density was lower when the treatment was applied. There were no significant treatment effects of irrigation (df = 1, F-value = 1.04, p-value = 0.3225), mowing (df = 1, F-value = 0.99, p-value = 0.3320) or grazing (df = 1, F-value = 0.01, p-value = 0.9076) on woody stem density.

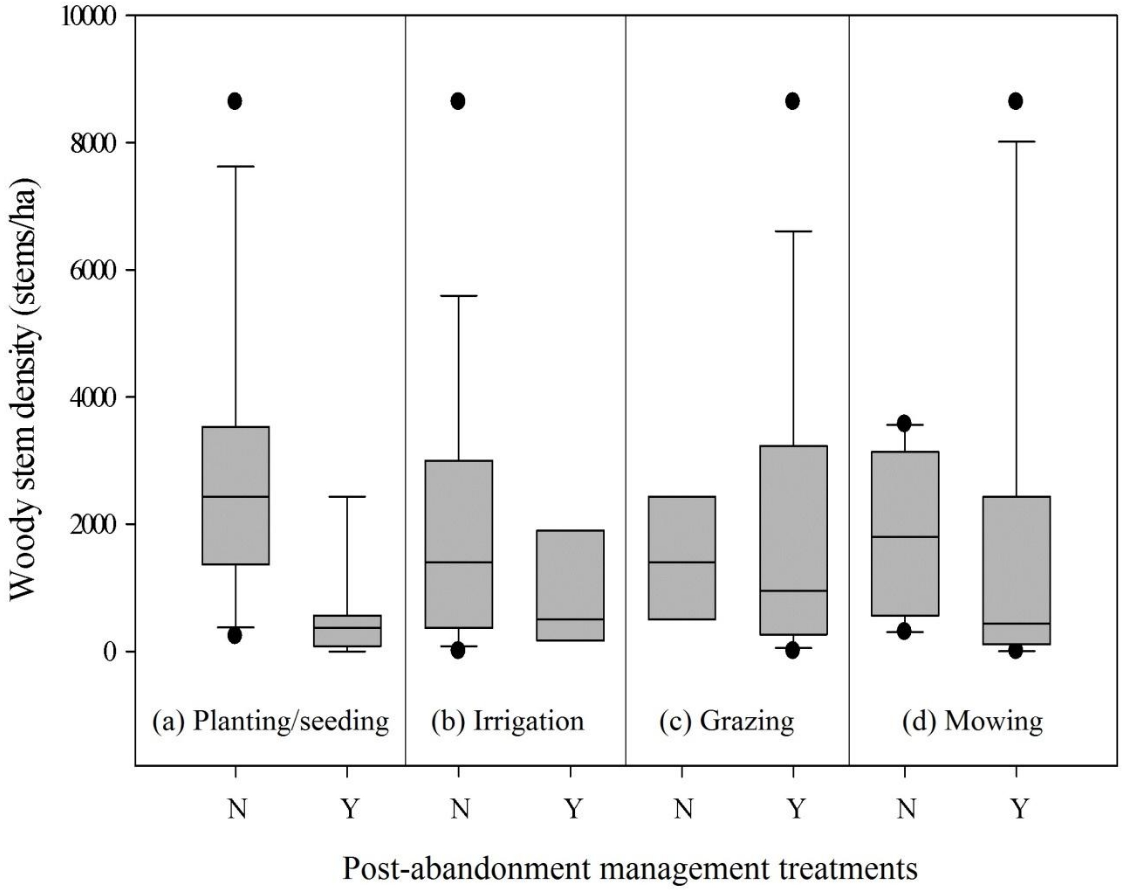

Figure 7. Woody stem density in abandoned agricultural fields as a function of restoration treatment. (a) N = not planted and/or seeded for restoration (*n* =11), Y = planted and/or seeded (*n*=9). (b) N = not irrigated for restoration (*n* =15), Y = irrigation was used (*n* = 5). (c) N = no grazing was allowed for restoration (*n* =7), Y = grazing was allowed (*n* =13). (d) N = not mowed for restoration (*n* =10), Y = mowing was performed (*n* =10).

Herbaceous Cover

In regression analysis, there was no effect of herbaceous cover on woody vegetation structure (Figure 8). When the effect of herbaceous cover (predictor variable) on basal area (response variable) was examined, there was not a significant relationship ($r^2 = 0.0121$, F-value = -0.47, p-value = 0.6443) (Figure 8). Herbaceous cover values were also used to evaluate relationships with stem density, and no significant relationship was found (r^2 = 0.0276, F-value = -0.72, p-value = 0.4837) (Figure 9). ANOVA indicated that post-abandonment planting and/or seeding treatment did not have a significant effect on herbaceous cover in abandoned agricultural fields (df = 1, F-value = 0.67, p-value = 0.4229, Figure 10).

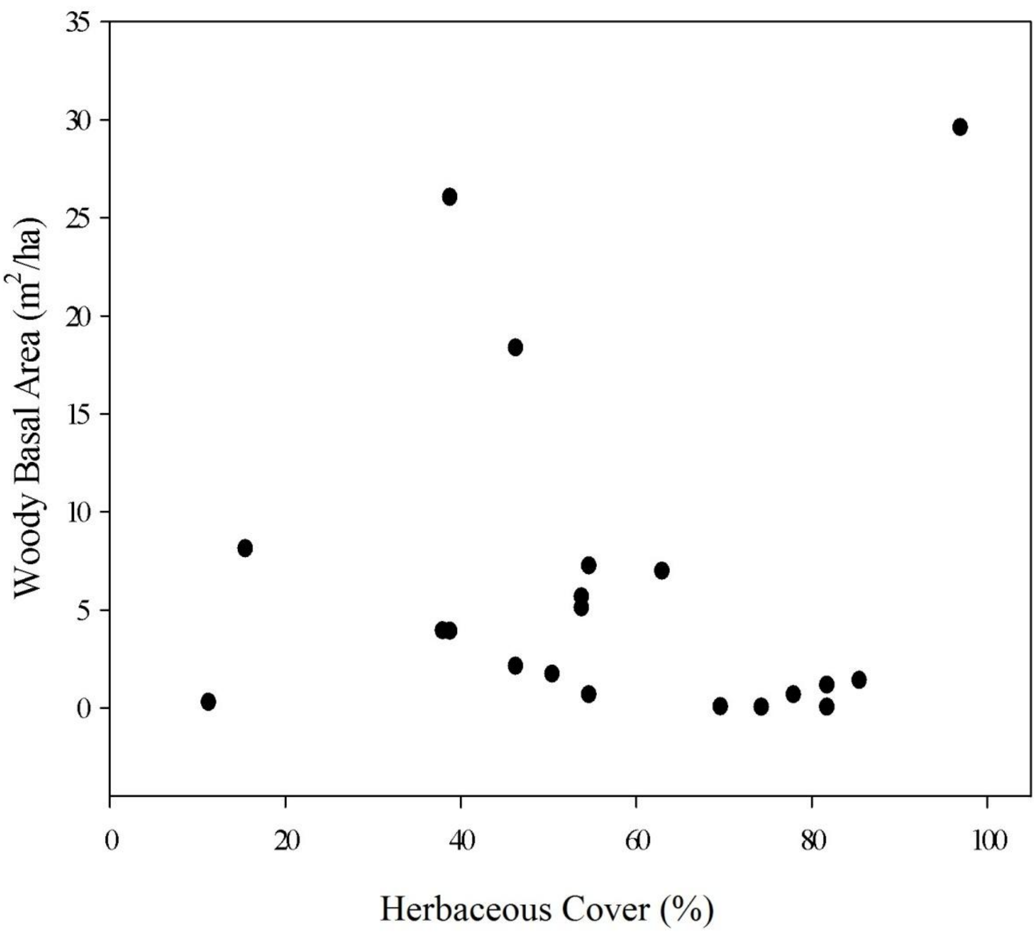

Figure 8. Relationship between herbaceous cover and woody basal area in abandoned fields in lower San Pedro River terraces (*n* = 20) fields.

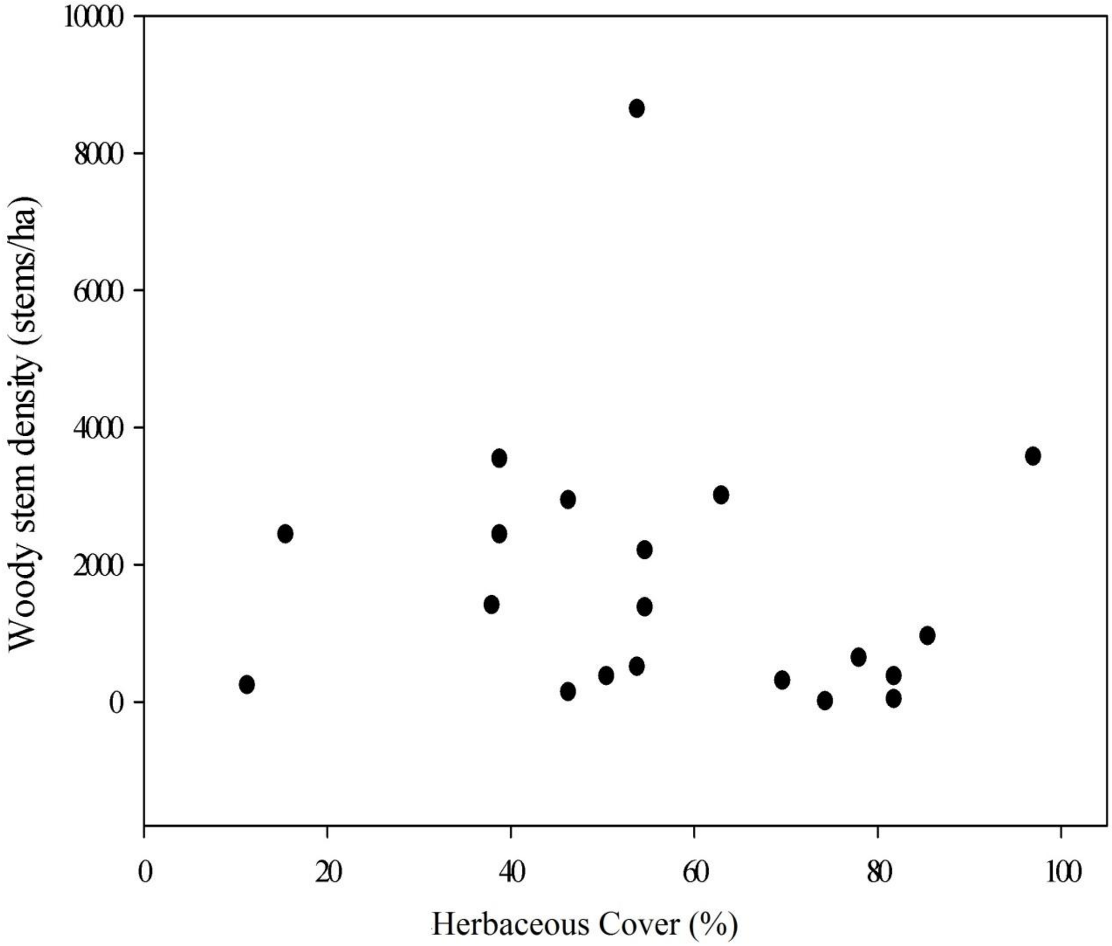

Figure 9. Relationship between herbaceous cover and woody stem density in abandoned fields in lower San Pedro River terraces (*n* = 20) fields.

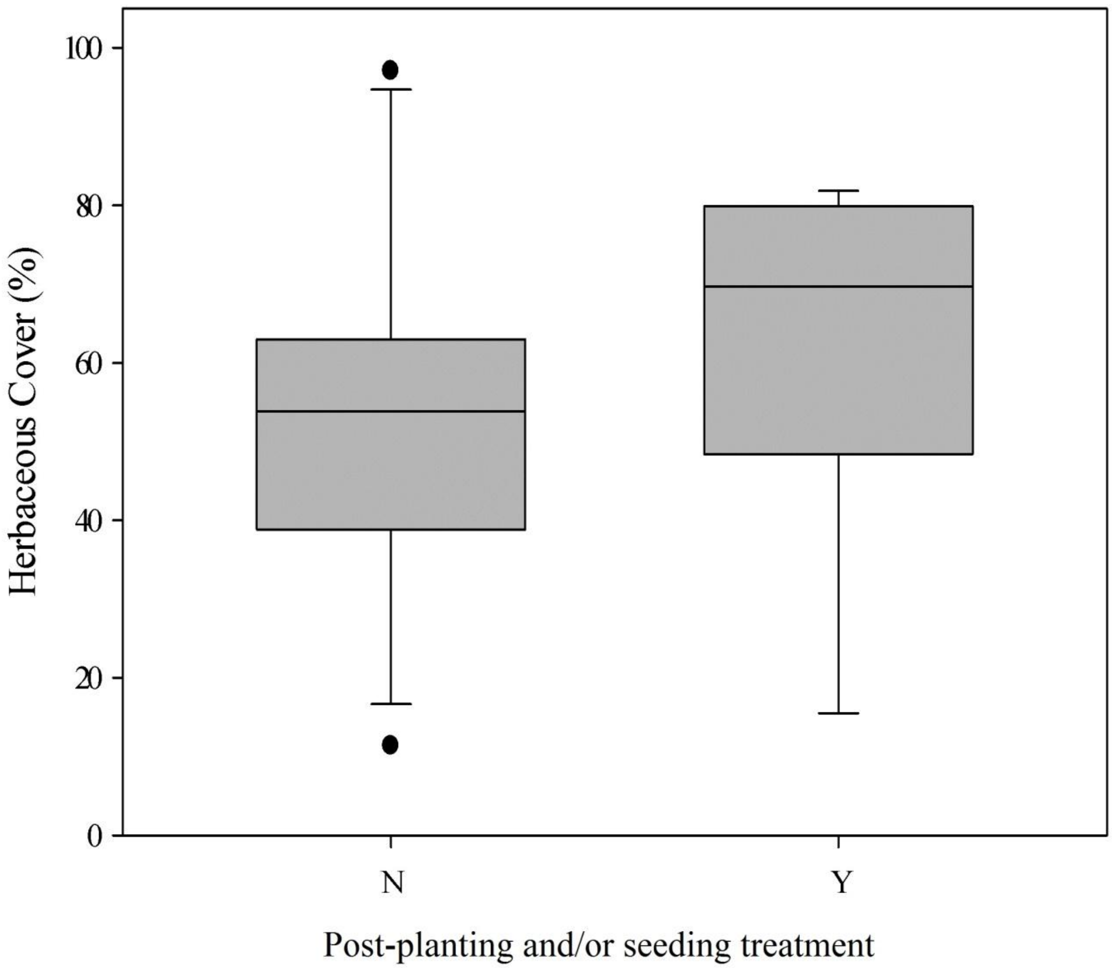

Figure 10. Herbaceous cover in abandoned agricultural fields as a function of post-restoration planting/seeding treatment. N = not planted/seeded for restoration (*n* =11), Y = planted/seeded (*n* = 9).

CHAPTER IV

DISCUSSION

a. Site-suitability analysis

In this study, site suitability analysis was used to successfully identify preliminary sites for field work. Use of this type of analysis allowed for informed decisions to be made *a priori* to prepare for fieldwork. Similarly, in the restoration literature, many researchers are using GIS and remote sensing imagery to identify, monitor, and determine suitable sites for restoration in many environments (Russell et al., 1997; Rohde et al., 2006; Malmstrom et al., 2008). For example, one recent study by Malmstrom et al. (2008) sought to identify sites and quantify the effects of seeding restoration efforts in a California rangeland. When used for restoration, site-suitability analyses were useful because they allowed a researcher to use defining criteria to solve a problem. In another GIS study, Rohde et al. (2006) used multiple limiting criteria to restoration to produce a site-suitability analysis for floodplain restoration in Switzerland. In this study, they used filters to determine restoration criteria and to quantify land area where restoration might be successful. Filters included ecological restoration criteria such as biodiversity measures, and distance to floodplain, presence of particular species, and other variables. Their analysis was a successful and valuable tool that enabled visualization of locations where floodplain restoration might be best suited.

Similarly, this study points to the usefulness of GIS in restoration projects and decision making.

The accuracy assessment results from the GIS site suitability analysis indicated that the output layer "Fields" yielded a reliable assessment of where suitable lands for restoration are located, and where field work could be conducted. Error matrix results for the "Fields" suitable layer yielded high Producer's accuracy, or low omission errors. Producer's accuracy (also known as omission error), is defined as the probability of suitable or unsuitable lands being correctly classified in an analysis (Jensen, 2005). For both layers, the accuracy is high, meaning that the "Fields" layer created in this analysis will correctly classify suitable lands almost all of the time.

However, the commission error for the "Fields" layer for suitable and unsuitable lands is lower when compared to the "MTFields" layer and the orthophotos. Commission error, also known as the User's accuracy, can be defined as the reliability that what is classified as suitable or unsuitable indeed represents that category (Jensen, 2005). This means the "Fields" layer classified real, suitable lands as actually being suitable most (74%) of the time. When assessing the accuracy of unsuitable lands, the "Fields" layer also yielded a good (66%), though lower Producer's accuracy to "MTFields." However, when unsuitable lands *are* classified, the likelihood or reliability in which the area classified actually represents that category is high (97%). This means a strict interpretation of what unsuitable land is defined as is being used in this project.

In the model, are willing to forgo increased Producer's accuracy of the "Fields" layer showing unsuitable lands, because one can be assured that if lands are classified as unsuitable, they will almost always be unsuitable in nature. This is due to the strict land cover criteria used in the model. What will result is that the model will sometimes over-classify suitable lands. As in all models, caveats remain, and use of a combination of field knowledge in conjunction with the model can help overcome imperfections. The errors present in this model are accepted because the analysis uses commonly available layers and employs a basic and fundamental GIS modeling approach that can be used by researchers and land managers alike. In order to improve on the model, more criteria would need to be used, which is possible but is likely to complicate the model and render it less user-friendly.

A primary reason results were less accurate in the “Fields” layer likely stems from the coarse resolution of the data used in the analysis, as coarser resolution data was used to develop the “Fields” layer. In GIS modeling, choosing too coarse of a resolution may obscure patterns and cause analyses to be less accurate (DeMers, 2002). The “MTFields” layer was likely more accurate than the “Fields” layer overall because M. Tluczek used 1 meter orthophotos as the basis for her hand-digitizing efforts (M. Tluczek, 2010, e-mail message to author). She also used her knowledge of area vegetation, which she acquired through field visits to the San Pedro River. In contrast, the “Fields” site suitability analysis was performed remotely and without prior field knowledge. The “Fields” layer was based primarily on the NLCD land cover layer only available at a 30 meter resolution, and other data layers at varying 1-500 m resolutions. Ultimately, all layers used to make “Fields” were converted to 30 meter resolution for accuracy reasons. The conversion from 1 meter to 30 meter resolution for the vegetation data likely caused details to be fuzzy and classification to be obscured, particularly around the edges of suitable and non-suitable areas.

In all, the classification was helpful in the identification of field sites suitable for restoration. However, the 500 meter resolution data layer probably limited the accuracy of the analysis due to the coarse resolution. If possible, pixel resolution for all layers should be one-half of the size of the smallest object mapped (DeMers, 2002). This means that pixel resolution should be one-half of the size of the smallest field, or perhaps even finer to accurately capture small sections of woody vegetation on fields. The smallest field was 1.64 ha (an area of 16400 m^2) at Bingham Cienega #1, so the minimum a pixel size could be is 0.82 ha (8200 m^2), or 90 meter resolution for all data layers. This means that the 500 meter natural vegetation layer was not ideal for this study. Future improvement on this analysis would involve using more fine resolution land cover layers below 90 meters, which would likely yield more accurate results.

Additionally, the conversion of the 500 meter resolution data to 30 meter resolution for the natural vegetation layer likely obscured results. However, when using publicly available data, often resolutions are not ideal and resolution might need to be changed to fit the needs of the project. In this project, obtaining freely available data that organizations can easily obtain and use with some accuracy was a primary objective, which is why resolutions were changed from 500 meters to 30 meters to better fit study sites and not interfere with the other data that was available at a finer resolution. However, converting coarse resolution data to a finer pixel size can portray the data is if it was known at the 30 meter scale. This action could have affected the edges of suitable and non-suitable areas, muddling edge results as contributing to some inaccuracy in the project.

b. Overview of general field conditions

Vegetation

All the fields sampled had relatively low woody species richness. Though the fields tended to have low woody stem density and low woody basal area, a few fields appeared to be on a trajectory of recovery. For example, 3 Links #5 had relatively high stem density, and the highest species richness, with 4 of 7 total species identified found on-site (Table 6). Fields that appeared to be in early stages of recovery were also located close to terrace vegetation (25 m away).

Prosopis velutina was the dominant woody species in all of the abandoned fields sampled. Prevalence of *P. velutina* on the fields could mean that mesquite bosque vegetation, found on terraces following arroyo downcutting of the late 19th century, is returning (Webb and Leake, 2006). Mesquite was once the most abundant riparian vegetation type and habitat in the Southwestern U.S., comprising approximately 60% of vegetation along the San Pedro River (Stromberg, 1993). In sampled San Pedro River fields, such strong presence of *P. velutina* growth and repopulation could be a sign that some field sites are beginning recover to native vegetation.

Soils

Soil characteristics were similar across all fields, and were composed of primarily sand and silt. Field soil texture can be described as sandy loam, loamy sand, or sandy texture (Buol et al., 2003). In the field soils were dry and compacted in the ground, but structureless once removed with an auger. Such homogenous soil characteristics can likely be attributed to long-term anthropogenic land use (Homburg and Sandor, 2010). These conditions are typical and have been found along the San Pedro River, as well as other arid region rivers in the Southwest (Homburg and Sandor, 2010).

Field soils were characterized by medium to high salinity. Limited terrace flooding, high temperatures, low precipitation, and high evaporation rates in these soils might have caused salt accumulations in soils that could impede vegetation growth and irrigation effects (Green et al., 2009). Soil salinity is also important to consider in the context of semi-arid restoration. For example, Beauchamp and Shafroth (2011) found that soil salinity affected plant community composition on riparian terraces in New Mexico. Specifically, they found that plant communities for each field establish based on soil salinity and soil texture. In addition, Bay and Sher (2008) found soil salinity to be an important predictor of invasive species success in their evaluation of 28 restoration sites in Arizona, Nevada, and New Mexico. In their regression model, they found that increased soil salinity contributed to *Tamarisk ramosissima* (Saltcedar) establishment at restoration sites. Perhaps on the San Pedro River, soils are not well-suited for some plant species. Increased soil salinity could be affecting soils and inhibiting native vegetation communities from flourishing, as native species have been found to thrive in lower salinity soils in nearby New Mexico (Beauchamp and Shafroth, 2011).

Additionally, soil compaction could impede vegetation structure and growth. All field soils were compacted when excavated from field sites. The compacted nature of the terrace soils, especially the hard surface, might contribute to decreased soil porosity (Homburg and Sandor, 2010). Additionally, inability of seeds to penetrate the surface, and overall persistent soil degradation have likely resulted from compaction (Hamburg and Sandor, 2010).

Degraded soil conditions are likely hindering restoration efforts, as Hobbs and Suding (2008) found plant-soil interactions to be the most important primary process affecting vegetation recovery, after disturbance and seed limitation.

c. Predictors of vegetation structure in fields

On the San Pedro River, several factors were found to have relationships with woody vegetation structure in abandoned terrace agricultural fields. In our regression model, distance to terrace vegetation, amount of clay in the soil, and whether planting and/or seeding was used for restoration were the primary factors affecting woody basal area. Field area, length of time (years) fields were farmed, and years since field abandonment were significant predictors of woody stem density. ANOVAs indicated that the only management treatment that had significant effects on woody stem density or basal area was planting and/or seeding. No other management variables had a significant effect on woody vegetation structure, and herbaceous cover did not have a significant effect on woody vegetation. From these results, it is apparent that the factors affecting vegetation recovery and restoration outcomes are multiple and complex. Thus, it is important to consider how these factors affect vegetation, and how they might be important to future restoration success on abandoned agricultural fields.

Vegetation factors and distance to seed source

In our study, distance to terrace vegetation, an important seed source, was a significant predictor of woody basal area in abandoned agricultural fields. Seed limitation and distance to seed source have been found to greatly affect post-disturbance recovery (Suding and Hobbs, 2008b; Cramer et al., 2007). For example, Pueyo and Alados (2007) found that distance to seed source significantly affected vegetation recovery and succession in arid old fields in the Middle Ebro Valley, Spain. Their model found increased distance to seed significantly hindered vegetation growth, more so than land use, water availability, or other factors. Thus, seed source could be significantly limiting new vegetation growth on San Pedro River field sites.

Dispersal is an important to consider in the context of limiting factors because dispersal can be variable in nature. Bakker et al. (1996), Thompson et al., (1993) and Bekker et al., (1998) indicated that weight and size of the seed largely determines the distance seeds can travel as well as seed persistence in any seed bank. According to Bekker et al. (1998), because woody plant seeds are larger, they are more likely to be transient in nature, short lived, and dispersed on the soil surface. They also argue that larger seeds are not as likely to be persistent in the seed bank, as their size makes it difficult for the seeds to infiltrate into the soil seed bank. However, Bakker et al. (1996) indicated that animal dispersal is one way in which any size seeds, not only small, light seeds, can travel from meters to kilometers in distance, as animals can disperse seeds long distances.

Seed dispersal and distance to seed source are likely influencing the vegetation present on field sites. This is possibly why at H&E #1, the field located farthest away (250 m) from terrace seed sources, woody vegetation was not present. Woody species composition was limited to only *P. velutina* at sites located closest (within 25 m) of the river, with the exception of 3 Links #5, BHP Billiton #2, and SPRP #2 (Table 6, Table 8). This could indicate that *P. velutina* is one of the few species located close enough to the disperse seeds to fields. *P. velutina* produces seeds within seedpods that are several centimeters in length and drop to the ground from the tree (USDA-NRCS, 2011a). These are often eaten and dispersed by ground rodents (Cox et al., 1993). Possibly, the relationship between *P. velutina* and desert rodents is impacting *P. velutina* dispersal (Reynolds and Glendening, 1949; Cox et al., 1993; Bahre and Shelton, 1993). Reynolds and Glendening (1949) and Cox et al., (1993) state that *P. velutina* seeds are dispersed long and short distances by kangaroo rats in the Chihuahuan desert scrub. Animal dispersal by many different animals could be encouraging *P. velutina* vegetation growth on fields.

Field size

One of the perplexing results in the regression analysis was that field area had a significant positive effect on woody stem density in the multiple regression analysis. Restoration literature has not touched on density-field area relationships, with the exception of one study (Lencova and Prach, 2011). Lencova and Prach (2011) found that field area and time since abandonment significantly affected grassland vegetation in their restoration study in the Czech Republic. However, they found that vegetation cover increased in smaller fields, rather than in larger ones. They speculated that this occurred because colonization of small fields by surrounding vegetation could have been easier, causing more rapid vegetation development to occur in small fields.

The positive relationship between field size and woody stem density could be due to several factors. Field area can impact what White and Walker (1997) call “area-sensitive” plant species, which might be prone to extinction on small field sites because of a low reproductive output. They argue that spatial context can also affect animal seed dispersers and seed dispersal because they believe plants that are poor dispersers are less likely to reach smaller field sites than larger ones. Bell et al. (1997) argued that restoration and landscape ecology are linked, and that field size and proximity to recruitment sites are likely to affect the success of seed dispersal. If this is true, seed dispersal would affect woody plant growth and density. The data suggest that field size could be having such an effect, as field areas are quite variable—they ranged from 1.6426 ha at Bingham Cienega #1 to 60.3909 ha at 3 Links #2, with a mean field size of 15.1883 ha, where larger sites have higher densities.

Soil properties

In this study, the regression model indicated that the percentage of clay in the soil was one of the three primary variables affecting woody basal area. It is likely that the amount of clay in the soil could be an important indicator for soils because clay would yield more structure, and clay particles would expand, closing pores and holding more water in the soil than in sandier soils (Lauenroth et al., 1994; Oleksyszyn, 2001; Buol et al., 2003; Beauchamp and Shafroth, 2011). My findings are similar to Oleksyszyn's (2001) study on the upper and lower San Pedro River, where she found that clay content of soils were significant in determining vegetation cover on fields. Here, Oleksyszyn (2001) argues that clay content in the soil could contribute to increased water holding capabilities in San Pedro River soils, contributing to vegetation growth. Oleksyszyn (2001) also found that at study sites in which percent clay was highest that *P. velutina* basal area and canopy cover was high, which she also attributes to water availability in the soil. Additionally, Beauchamp and Shafroth (2011) found soil texture to be a significant predictor of plant community composition at reference sites in New Mexico, USA. They found that when they compared coarse textured soils to finer textured soils different core plant communities persisted. This is also likely related to a change in water availability, caused by the clayey soil texture (Beauchamp and Shafroth, 2011).

Soil texture has also been found to influence plant establishment and recruitment in semi-arid to arid environments. For example, Lauenroth et al. (1994) found that soil texture greatly influenced the rate of recruitment of grasses in the Central Plains Experimental Range in Colorado, USA. Particularly, they found that those soils considered sandy were found to have a significantly lower recruitment rate of grassland vegetation per year compared to soils of more silty and clayey textures of much higher recruitment rates. This is probably because the clayey soils hold more water in relation to silty and sandy soils, which have larger pore spaces that water can infiltrate. Soil texture and compaction of the surface can play a large role in seed establishment for *A. constricta* and *P. velutina* (Cox et al., 1993). For example, in their study in the Sonoran desert, Cox et al. (1993) found that the majority of *A. constricta* and *P. velutina* seedlings did not emerge from the soil when the soil types were of silty clay loam. They also found that *P. velutina* emerged 95-100% of the time, while *A. constricta* emerged 57-77% of the time when planted in sandy loam 1-2cm from the soil surface. They also found that all plant seeds were unsuccessful and could not break through the soil when compacted. Soils on the San Pedro are considered to be either a sandy or coarse loamy texture. Thus, it is apparent that texture could be influencing establishment of plants and might explain the high numbers of *P. velutina* on fields, as argued by Oleksyszyn (2001) and Cox et al. (1993) and as the data suggest in this study.

Agricultural history

The history of agricultural land use significantly influenced woody vegetation structure of abandoned fields in our study. In our regression model, the number of years fields were farmed was a significant positive predictor of woody stem density. For example, 3 Links #5 was farmed for the longest period of time, 120 years (Table 9). This field also had the highest recorded stem densities of any fields sampled. This is perplexing, because it would seem that fields with longest agricultural histories would be most impacted and would therefore resist plant growth most (Cramer et al., 2007; Standish et al., 2007).

Additionally, time since abandonment was significant positive predictor of stem density. For example, 7B #1 and 7B #2 have been abandoned for the longest period of time of all field sites (Table 9). These fields also had some of the highest recorded stem densities. These findings are contrary to a similar study on the upper and lower San Pedro River where Oleksyszyn (2001) did not find time since abandonment to be a primary factor affecting vegetation structure and successional change on the river, though this factor was found to explain species variation on fields. Additionally, Oleksyszyn (2001) found that basal area of *P. velutina* did increase with time since abandonment, which was not a finding in this study. However, *P. velutina* was the most common woody species found on San Pedro River fields, and this species contributes most of the woody stem density and basal area measured.

Additionally, other literature has found time since abandonment to be a significant, such as in one study that took place in Mount Cameroon, Cameroon, Africa. There, Ndam and Healey (2001) found that woody density was highest in abandoned fields that were at least 30 years old. They also found that woody density was lowest in fields that had been abandoned for 3-5 years. In applying Ndam and Healey’s (2001) findings to old fields on the San Pedro River, it would make sense that the older the field, the higher the woody plant density would be on field site. This is likely because these fields had the longest amount of time to recover from past agricultural use.

Additionally, fields could be exhibiting the beginning of a delayed successional trajectory where limited species colonize the fields, rather than a persistent degraded state, where likelihood of recovery is lower (Cramer et al., 2007). For example, Bonet and Pausas (2004) found that in arid region old fields in southeastern Spain that woody species continually increased with age over a 60 year time since abandonment gradient. They also found that perennial forbs and grasses peaked in earlier years, at around 10-25 years following abandonment. Bonet and Pausas' (2004) findings indicate that while forbs and grasses will re-vegetate an area within a decade or two after abandonment, woody species will need many years to establish, and fields will likely take decades or more to fully recover. This is because time is a significant factor affecting vegetation growth and restoration on abandoned semi-arid fields (Suding and Hobbs, 2008).

Management treatments

Post-abandonment management treatments such as irrigation, grazing, and mowing had little influence on the woody vegetation response variables, according to regression analysis and ANOVA results. Perhaps most management treatments were unsuccessful in jumpstarting ecosystem recovery, because abiotic and biotic factors such as soils, seed limitations, or agricultural legacies were influencing vegetation response (Cramer et al., 2007). However, our regression model found that planting and/or seeding treatment was one of the three primary factors affecting woody basal area. Interestingly, the model found that the use of planting and/or seeding treatments negatively affected woody basal area. That is, where planting and/or seeding was used, woody basal area decreased on fields.

Perhaps one reason for the negative relationship is that the planting and seeding performed was herbaceous plantings, rather than woody. One example of herbaceous plantings is at the Bingham Cienega site, where Sacaton grass and sunflowers were once planted. Herbaceous cover was also recorded as high at Bingham Cienega. Perhaps these plantings enabled herbaceous growth and inhibited establishment and survival of woody seedlings, as there was an overall trend in the data that herbaceous cover seemed to increase when post-planting and seeding treatments were applied. However, ANOVA did not indicate these differences were significant (Figure 10). Another reason why restoration planting and/or seeding might have had a negative relationship with woody basal area was that perhaps planting/seeding treatments were only implemented in problem fields. That is, the seeds were applied as a response to observed low rates of native plant recovery.

d. Implications for restoration

The low woody basal area and stem density measured at most field sites indicates an overall lack of vegetation growth, which is probably inhibited by a combination of environmental factors. Agricultural legacies persist in San Pedro River field sites, and the legacy of past land use is likely a significant factor affecting ecosystem recovery. This is likely because all fields have been farmed for decades, though some have been farmed a century or more. Both of the agricultural variables tested in the regression models, years farmed and years since abandonment, were found to be a significant predictors of woody stem density. In the literature, arid region studies have found that historical agricultural practices were the cause of significant land degradation, which often causes fields to be stuck in a persistent degraded state (Cramer et al., 2007; Suding and Hobbs, 2008b). Since terrace fields on the San Pedro have extensive agricultural histories of disturbance, agricultural histories likely play a role in vegetation structure, as well as future recovery, on the San Pedro River.

Loss of seed banks from agricultural land use is likely contributing to restoration difficulty. On the San Pedro River, distance to seed source, or distance to nearby vegetation, could be a limiting factor, especially for woody plants. This is because seed banks likely do not hold much native vegetation seed, so field re-vegetation is dependent upon nearby vegetation to disperse seed to the fields. Despite this obstacle, some fields that were located close to terrace vegetation appear to be in early stages of recovery. Field size is also an indicator of woody density, though future work could expand on and investigate the question of why larger fields might show higher density and basal area values than smaller fields.

Abiotic factors that affect soil structure or the physical environment, can limit recovery (Cramer et al., 2007). Soil salinity, pH, and texture can be altered by agricultural practices, and these factors are important to plant growth and recovery. In the regression models, only texture was found to be a significant predictor of woody basal area. However, it is likely that pH and salinity variables were not found to be significant in the regression models because all fields had similar values, not because these factors are not important. In the context of restoration, these findings could be important. Beauchamp and Shafroth (2011) point out that restoration should focus on "generalist" species that tolerate most conditions, meaning relatively high soil salinity, and different soil textures, in order to have the best chance of restoration success. Perhaps this information might benefit the future San Pedro restoration projects.

Old fields on the San Pedro River might require more active measures in the future to accelerate restoration. Perhaps significant fertilizer treatments are needed, such as in the case study by Cramer et al. (2007) explains regarding a restoration site in Western Australia, as researched by Standish et al. (2007). Here, Standish et al. (2007) state that original restoration treatments to soils had yielded little results, even though the site has been abandoned for decades. Other future work on this project could involve use of restoration reference sites to guide research. Such work has been completed in the past by Katz et al. (2009b), who used reference sites to target appropriate restoration conditions on the San Pedro. Reference site conditions could be helpful, because they can provide an idea of what types of vegetation are able to grow in an area. Reference sites are also helpful and provide managers the ability to identify specific native vegetation conditions and realistic restoration goals.

CHAPTER V

CONCLUSION

The desire to depart from an agrarian lifestyle has facilitated urbanization and industrialization in the U.S., causing rapid abandonment of agricultural lands in the 20th century. This is not just a problem in the United States, but an important global issue. This is because as we become an increasingly technology-driven society, abandonment of agricultural lands also has environmental implications in the 21st century. In North America, farmlands have been abandoned at high rates throughout much of the 20th century (Waisanen and Bliss, 2002). Agricultural land use and abandonment have the capacity to threaten our ecosystems because such land use contributes to species habitat loss, habitat fragmentation, and a general decrease in ecosystem services overall.

In order to determine field sites on the San Pedro River that were suitable for ecological restoration and for this study, a site suitability analysis was performed using GIS. In the past, GIS has provided the capacity to undertake site-suitability analysis in an economical and efficient manner. This suitability analysis yielded accurate and reliable results for identifying suitable terrace lands. However, the process was not perfect and some caveats remain, namely the coarse resolution of the data used. Coarse resolution ultimately caused the analysis to be less accurate than if finer resolution data were available. However, this data was representative of the data commonly available for this type of study, and could be used by The Nature Conservancy in future projects.

Once sites were chosen for study, data collection was completed. All variables were entered as predictor variables into two regression models—one model for the response variable of woody stem density, and one model for woody basal area. Many variables were significant in predicting woody vegetation and structure on the San Pedro River. Variables found to predict woody basal area included distance to terrace vegetation, percent clay in the soil, and post planting and/or seeding treatment. Variables found to predict woody stem density included field area, years farmed, and time (years) since abandonment. After assessing the data, it is likely that a combination of high evapotranspiration and low precipitation rates (arid climate), paired with degraded soils, altered soil seed banks, and distance to vegetation are inhibiting San Pedro terrace vegetation growth.

Results show that there are many things to be learned about San Pedro River fields. It is likely that many factors are at play here. Water availability could be a huge problem, for example. Compounded on known significant factors like soil, field area, planting/seeding, and vegetation, are agricultural legacy factors. Agricultural legacies often make it difficult for fields to recover, as restoration literature has shown. This is because fields could have crossed abiotic and biotic thresholds (Cramer et al., 2007). The crossing of these thresholds could be enforcing a feedback loop that causes the San Pedro River fields to remain degraded. This feedback loop is likely the reason fields resist restoration efforts.

Though fields have resisted restoration techniques in the past, there are positive implications for practicing restoration on fields along the San Pedro River. Restoration can have positive implications in that field managers can mitigate the effects of anthropogenic land use, which often destroys soil structure and strips seed banks of native seed sources. Undoing these effects can increase and promote biodiversity in the region. As the trend of depopulation of rural areas continues (Cramer et al., 2007), old farmlands will be left and native habitats can be reestablished, if conditions permit. Restoration practice gives managers the ability to restore fields and habitats that require action.

There must be an understanding of succession theory combined with restoration practice, in order to understand how each field can be restored. This is because restoration of abandoned agricultural fields is a multi-faceted, multi-scale problem, and all fields will not likely have similar characteristics or respond in the same manner to treatments. This brings home the argument of Cramer et al. (2008) that ecosystems are complex and that vegetation can be affected by many factors. Such factors provide layers of complexity to restoration practice, and the best approach may be a holistic one that considers successional theory, limiting factors, and restoration approaches/treatments that can affect vegetation structure.

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APPENDIX A

GIS Site-Suitability Analysis

Appendix A. Master Input Data List (Metadata) for the GIS site-suitability analysis.

File: natveg.shp
From: Arizona Land Resource Information System
Acquired: March 1, 2010
Format: shape file
Process description: Digitized from 1:1,000,000 paper map.
Source used: Brown and Lowe's "Biotic Communities of the Southwest"
Process date: 2004
Horizontal coordinate system:
Projected coordinate system name: NAD_1983_HARN_UTM_Zone_12N
Geographic coordinate system name: GCS_North_American_1983_HARN
Map Projection Name: Transverse Mercator
Planar Coordinate Information:
Planar Distance Units: meters
Geodetic Model:
Horizontal Datum Name: D_North_American_1983_HARN
Ellipsoid Name: Geodetic Reference System 80
Resolution: 500 meters

Files: FORTHE.sid, GLOBEW.sid, MAME.sid, MAMW.sid, TUCE.sid, TUCW.sid
From: Arizona Land Resource Information System
Acquired: March 1, 2010
Format: MrSID Orthophotos
Source used: NAIP
Process date: 2007
Horizontal coordinate system:
Projected coordinate system name: NAD_1983 _UTM_Zone_12N
Geographic coordinate system name: GCS_North_American_1983
Map Projection Name: Transverse Mercator
Planar Coordinate Information:
Planar Distance Units: meters
Geodetic Model:
Horizontal Datum Name: D_North_American_1983
Ellipsoid Name: Geodetic Reference System 80
Resolution: 1 meter

Files: Narrows_to_Gila_Floodplain.shp, Narrows_to_Gila_boundaries.shp, Narrows_to_Gila_veg.shp

From: Melanie Tluczek, Arizona State University

Acquired: April 1, 2010

Format: shape files

Process description: Digitized from Orthophotos of the San Pedro River.

Source used: 2003 1 m resolution FORTHE.sid, GLOBEW.sid, MAME.sid, MAMW.sid, TUCE.sid, andTUCW.sid orthophotos from the Arizona Land Resource Information System, by NAIP

Process date: 2009

Horizontal coordinate system:

Projected coordinate system name: NAD_1983 _UTM_Zone_12N

Geographic coordinate system name: GCS_North_American_1983

Map Projection Name: Transverse Mercator

Planar Coordinate Information:

Planar Distance Units: meters

Geodetic Model:

Horizontal Datum Name: D_North_American_1983

Ellipsoid Name: Geodetic Reference System 80

Resolution: 1 meter

File: landcover5_3k_022007.img

From: Multi-resolution Land Characteristics Consortium, National Land Cover Database

Acquired: April 19, 2010

Format: Remote sensing image (raster file).

Source used: Landsat Imagery

Process date: 2001

Horizontal coordinate system:

Projected coordinate system name: USA_Contiguous_Albers_Equal_Area_Conic_USGS_version

Geographic coordinate system name: GCS_North_American_1983

Map Projection Name: Albers Conical Equal Area

Planar Coordinate Information:

Planar Distance Units: meters

Geodetic Model:

Horizontal Datum Name: D_North_American_1983

Ellipsoid Name: Geodetic Reference System 80

Resolution: 30 meters

APPENDIX B

Coordinates of Field Sites

Appendix B. Latitude and Longitude of plots in each of the twenty field sites on the San Pedro River. Note that there are three 10 x 10 m plots per field.

Site Name	Field	Plot	Latitude	Longitude (-)
H & E	1	1	32.77347	110.66818
H & E	1	2	32.77295	110.66925
H & E	1	3	32.77262	110.66977
H & E	2	1	32.77102	110.66299
H & E	2	2	32.77102	110.66153
H & E	2	3	32.77164	110.66245
H & E	3	1	32.76998	110.66257
H & E	3	2	32.76870	110.66096
H & E	3	3	32.76889	110.66183
Clark Ranch	1	1	32.97531	110.78053
Clark Ranch	1	2	32.97623	110.78010
Clark Ranch	1	3	32.97652	110.78067
7B Ranch	1	1	32.71396	110.62129
7B Ranch	1	2	32.71437	110.62137
7B Ranch	1	3	32.71333	110.62123
7B Ranch	2	1	32.71294	110.62318
7B Ranch	2	2	32.71254	110.62251
7B Ranch	2	3	32.71211	110.62227
SPRP	1	1	32.92609	110.74287
SPRP	1	2	32.92507	110.74348
SPRP	1	3	32.92862	110.74477
SPRP	2	1	32.93412	110.74757
SPRP	2	2	32.93527	110.74786
SPRP	2	3	32.93625	110.74879
SPRP	3	1	32.92617	110.74063
SPRP	3	2	32.92631	110.74041
SPRP	3	3	32.92467	110.73900
Bingham Cienega	1	1	32.45750	110.48249
Bingham Cienega	1	2	32.45745	110.48296
Bingham Cienega	1	3	32.45646	110.48237
Bingham Cienega	2	1	32.46030	110.48495
Bingham Cienega	2	2	32.46062	110.48523
Bingham Cienega	2	3	32.46150	110.48530
Bingham Cienega	3	1	32.45854	110.48485
Bingham Cienega	3	2	32.45900	110.48420
Bingham Cienega	3	3	32.45845	110.48521
BHP Billiton	1	1	32.65318	110.59205
BHP Billiton	1	2	32.65279	110.59049

Appendix B. Latitude and Longtude (continued).

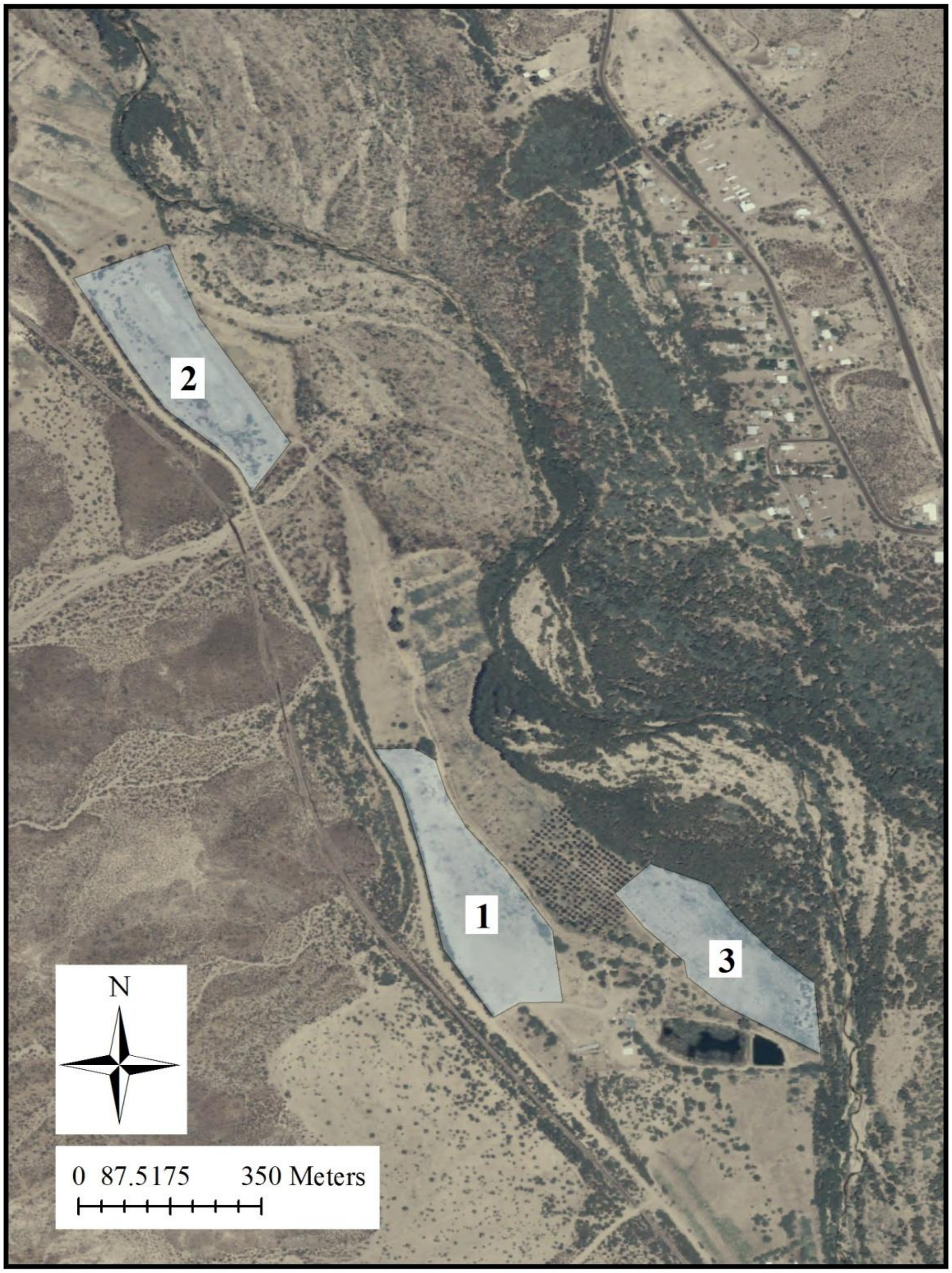
BHP Billiton	1	3	32.65159	110.59034
BHP Billiton	2	1	32.65469	110.59292
BHP Billiton	2	2	32.65422	110.59243
BHP Billiton	2	3	32.65441	110.59169
BHP Billiton	3	1	32.64585	110.58573
BHP Billiton	3	2	32.64532	110.58359
BHP Billiton	3	3	32.64561	110.58510
Three Links	1	1	32.15628	110.28901
Three Links	1	2	32.15659	110.29053
Three Links	1	3	32.15794	110.29375
Three Links	2	1	32.17161	110.29953
Three Links	2	2	32.17289	110.29812
Three Links	2	3	32.17304	110.29934
Three Links	3	1	32.19238	110.30576
Three Links	3	2	32.19112	110.30409
Three Links	3	3	32.19188	110.30352
Three Links	4	1	32.19757	110.30692
Three Links	4	2	32.19819	110.30950
Three Links	4	3	32.19698	110.30890
Three Links	5	1	32.18515	110.29707
Three Links	5	2	32.18618	110.29950
Three Links	5	3	32.18747	110.29920

APPENDIX C

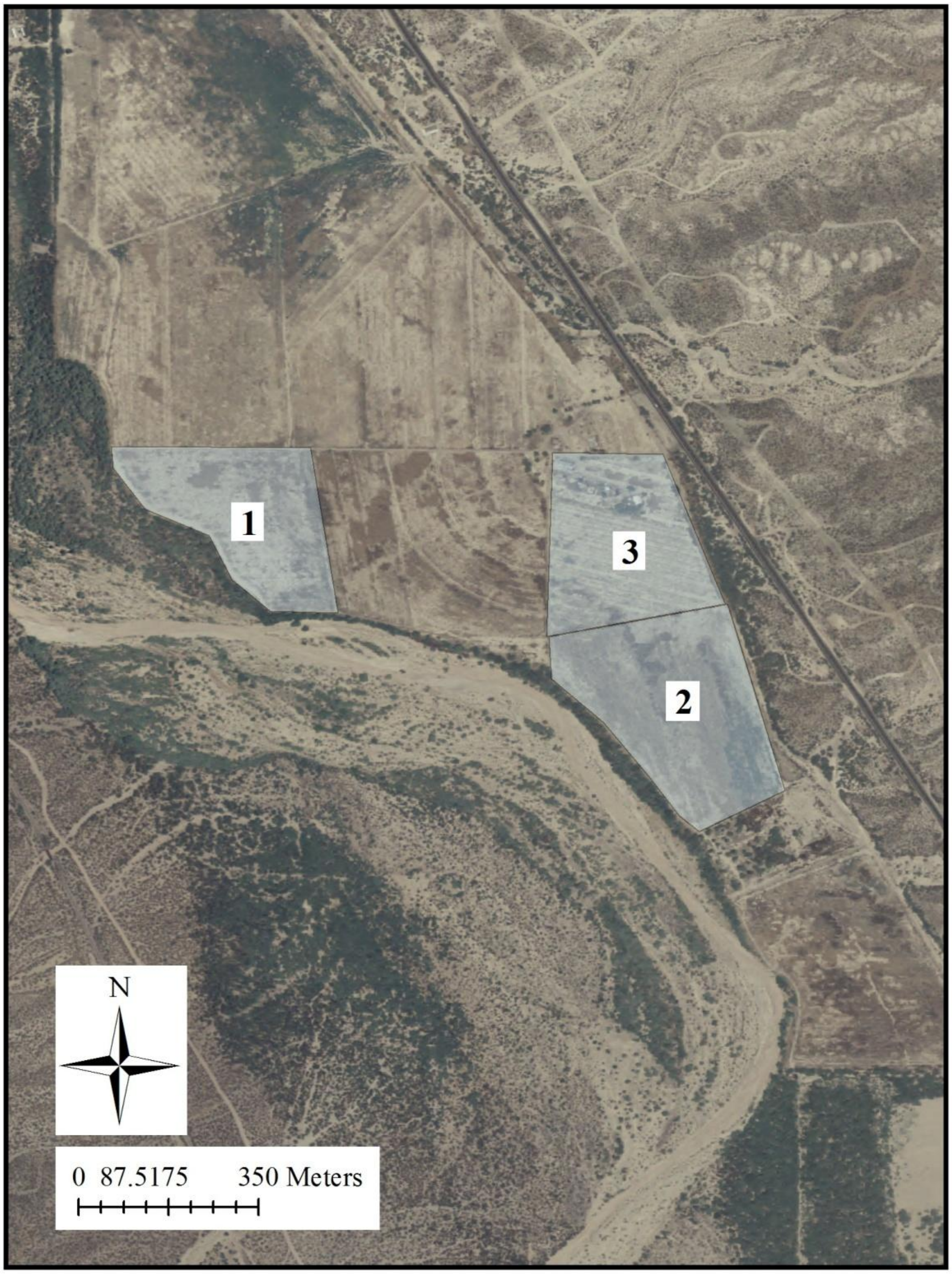
<u>Maps of Field Sites</u>

Appendix C. Map of the Clark Ranch field, located on the lower San Pedro River.

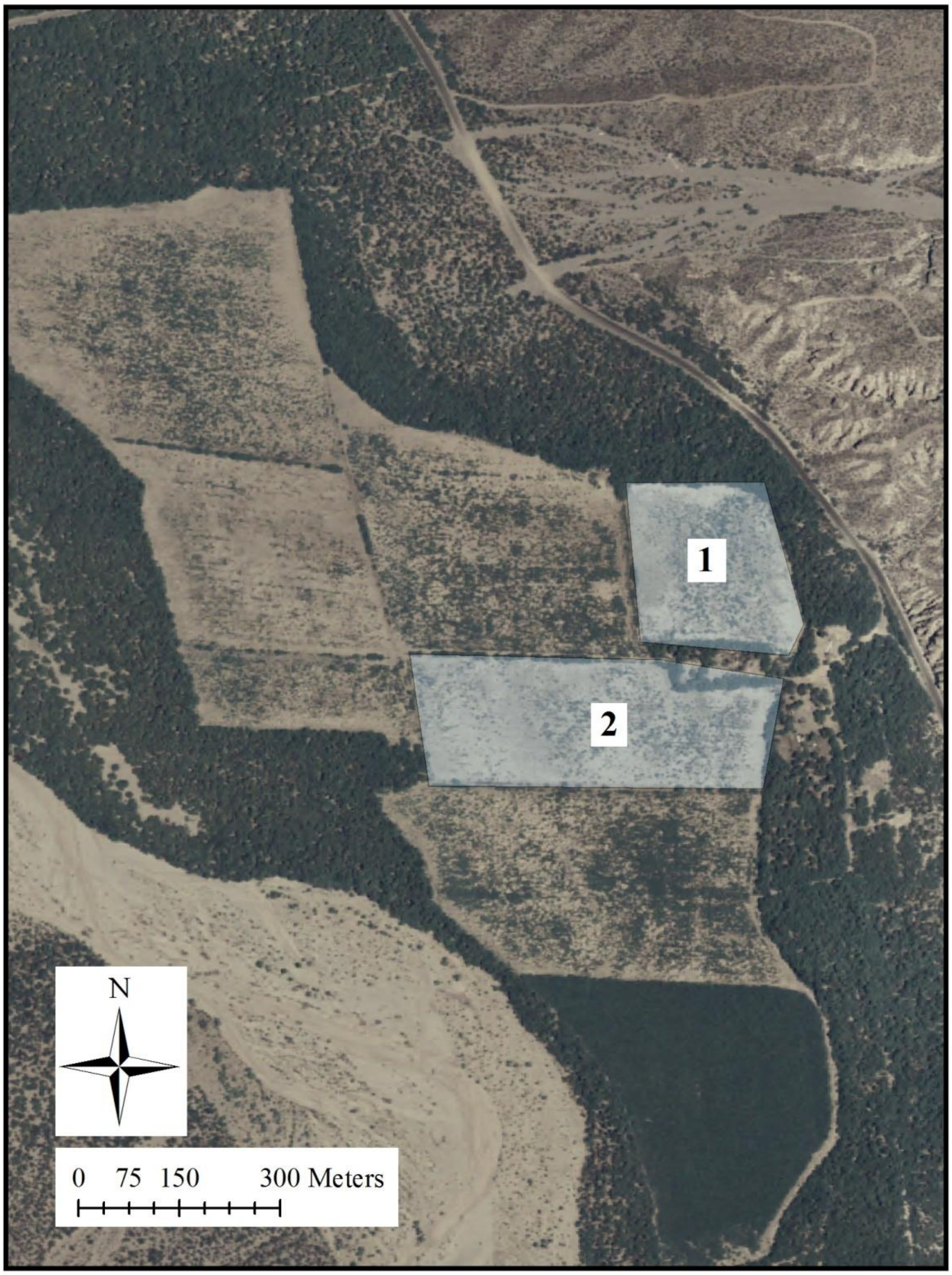
Appendix C. Map of San Pedro River Preserve fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



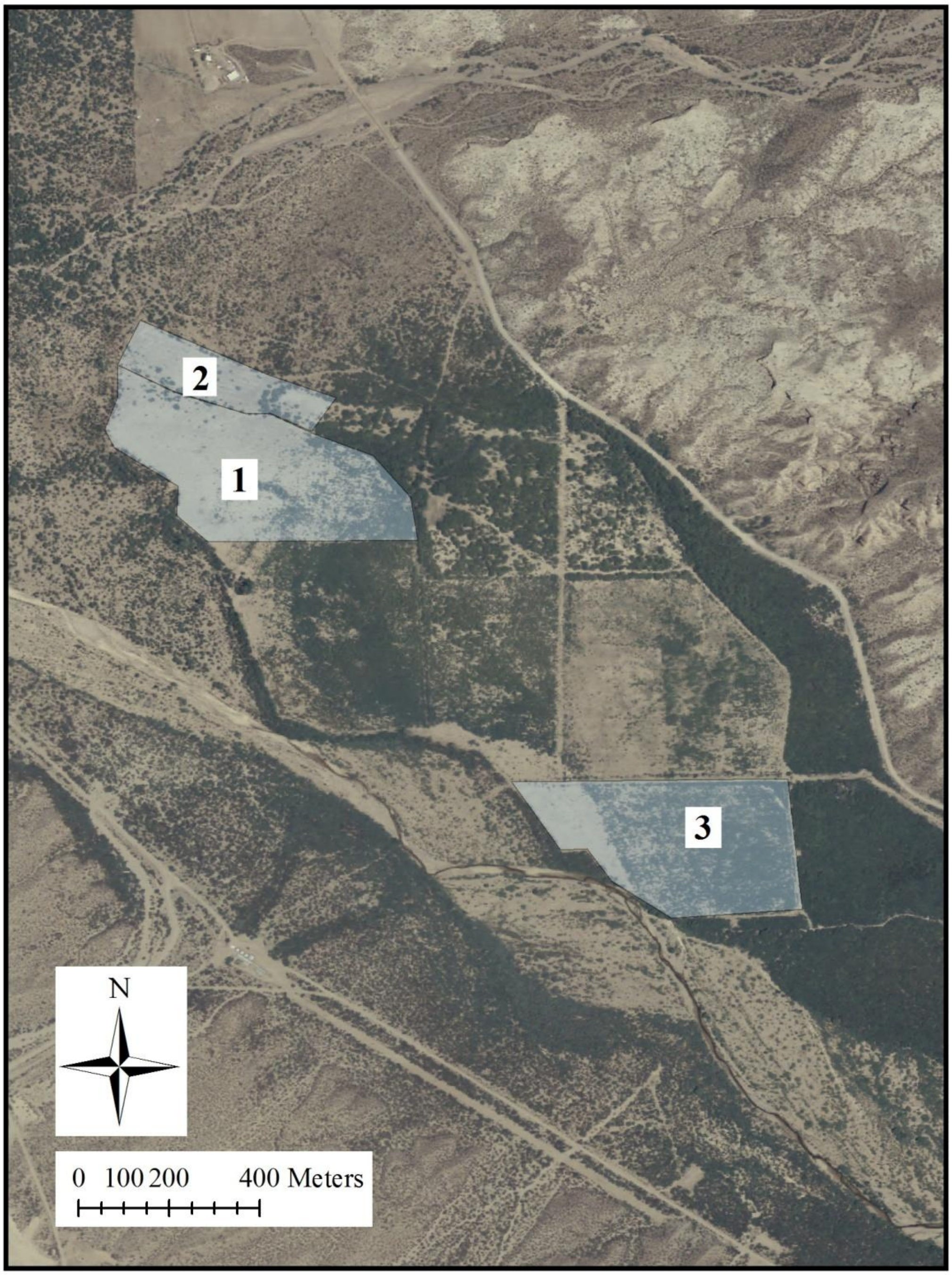
Appendix C. Map of H&E Farm fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



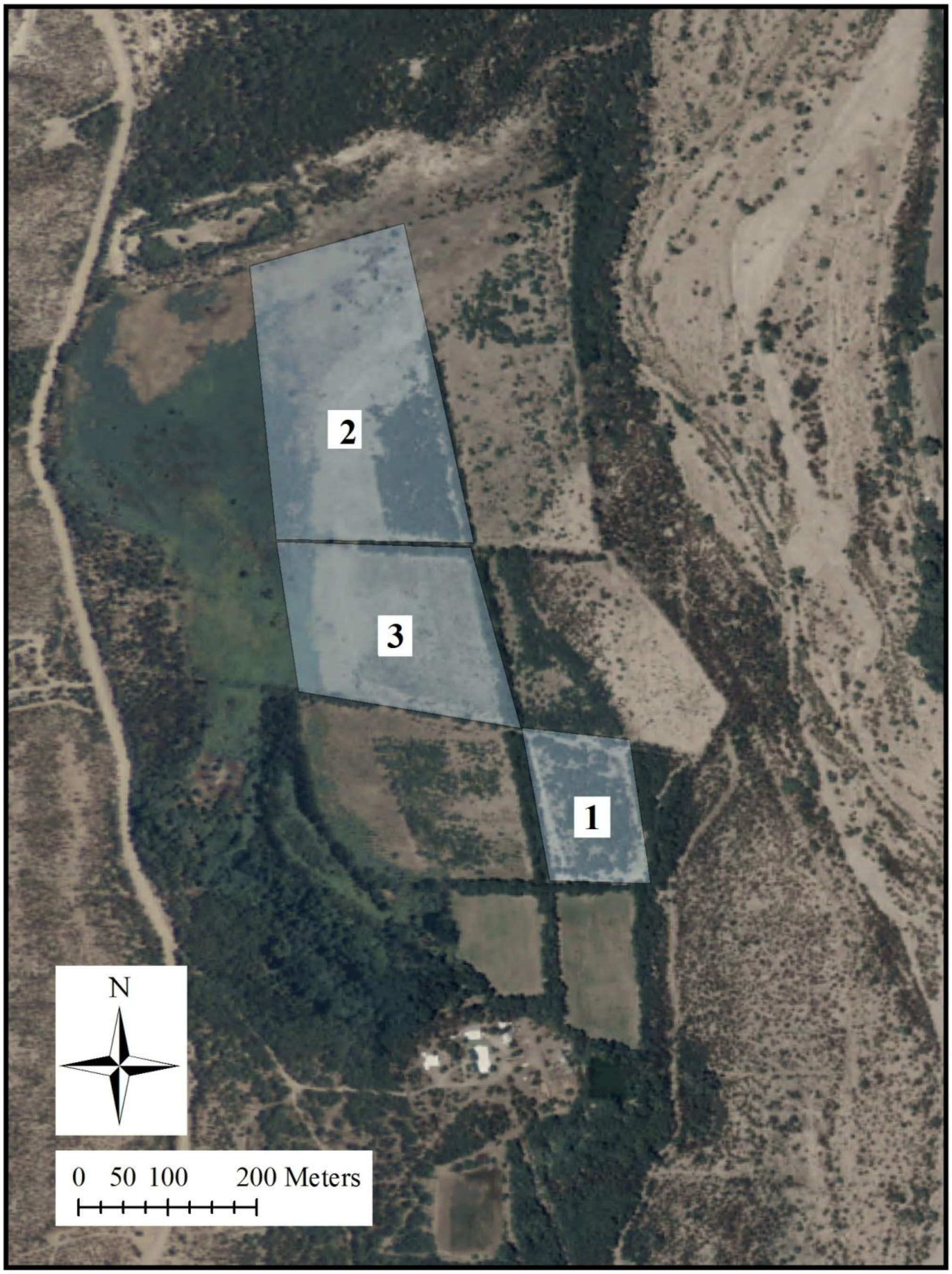
Appendix C. Map of 7B Ranch fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



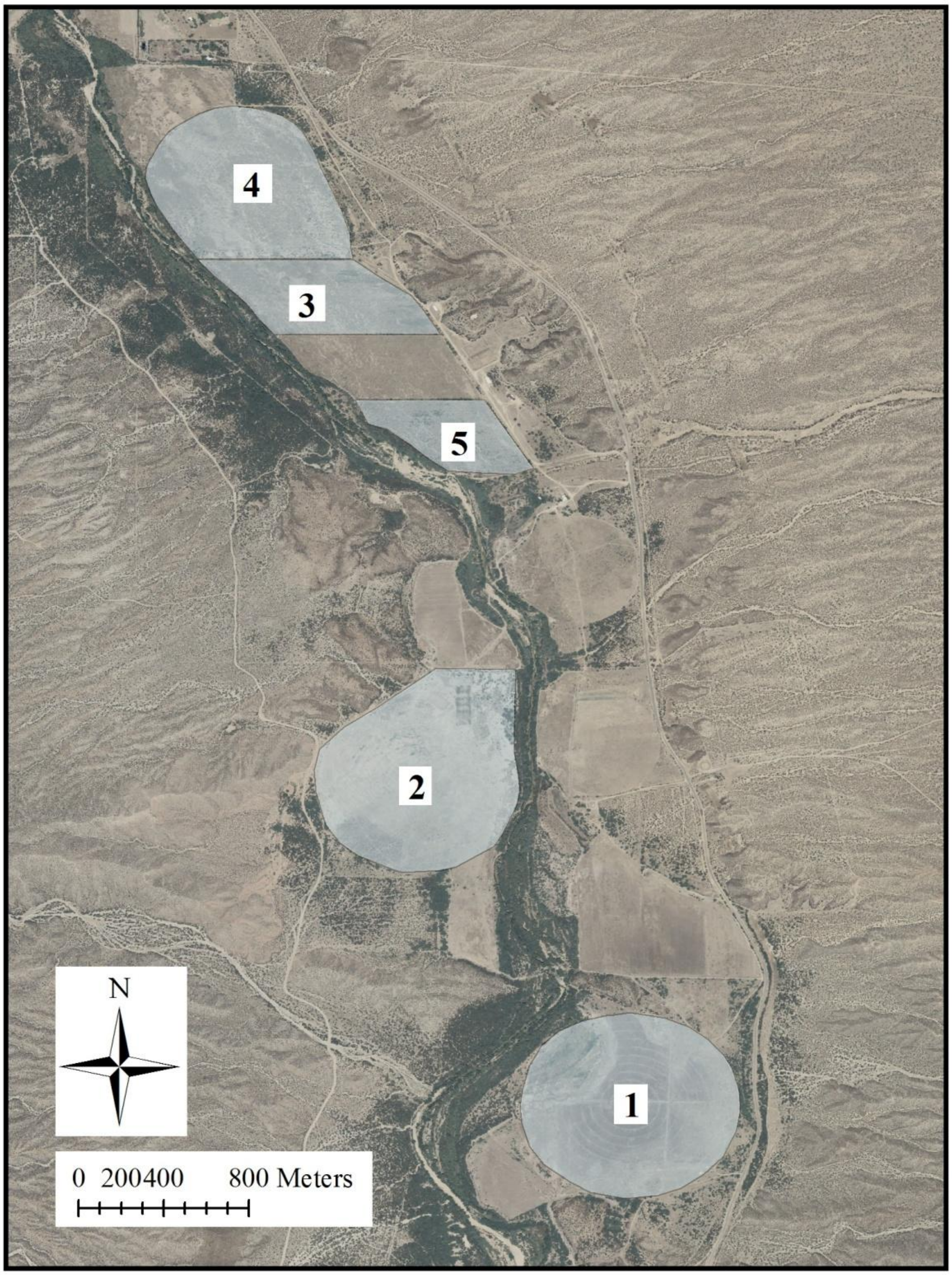
Appendix C. Map of BHP Billiton fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



Appendix C. Map of Bingham Cienega fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



Appendix C. Map of Three Links Farm fields, located on the lower San Pedro River. Fields are labeled by field site number where indicated.



VITA

Carla Mae Gray was born in Tampa, Florida on April 20, 1987. Carla lived in both Tampa, Florida and in Wilmington, North Carolina throughout her childhood. As a child, she always enjoyed the natural and social sciences. After she finished high school at Eugene Ashley High in Wilmington, North Carolina in 2005, Carla attended the University of North Carolina, Wilmington for undergraduate studies from 2005-2009. There, she worked on a thesis involving soils and land use change on the Cape Fear River floodplain. In 2009, she was awarded a B.A. in Geography at UNC Wilmington.

During her time at UNC Wilmington, Carla also interned with the New Hanover Soil and Water Conservation District in Wilmington, North Carolina. There, she helped teach environmental education to eighth grade students and focused on environmental stewardship programs and community outreach. Carla thoroughly enjoyed her work at the internship, where she worked with the general public and local city council and county commissioners to promote environmental stewardship. This internship helped Carla realize that she wanted to pursue an advanced degree in Geography, where she could focus on environmental and ecological topics. Following graduation from UNC Wilmington, Carla attended graduate school at Appalachian State University from 2009-2011 for Geography. At Appalachian, Carla’s primary focus was on the topic of ecological restoration in arid regions. In 2011, Carla was awarded an M.A. in Geography at Appalachian State University.

In the future, Carla hopes to merge her academic experiences and personal interests in order to work toward a Juris Doctor degree. Carla's time at Appalachian has convinced her that she should become an environmental advocate, a goal she hopes to attain through the study of the law. Carla wants to pursue a J.D. concentrating on environmental and non-profit law. In this way, she can combine her academic background and her focus on environmental issues with the practice of law.