Sustaining Irrigation Agriculture for the Long-Term:

Lessons on Maintaining Soil Quality from Ancient Agricultural Fields in the Phoenix Basin and on the North Coast of Peru

by

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ABSTRACT

Irrigation agriculture has been heralded as the solution to feeding the world’s growing population. To this end, irrigation agriculture is both extensifying and intensifying in arid regions across the world in an effort to create highly productive agricultural systems. Over one third of modern irrigated fields, however, show signs of serious soil degradation, including salinization and waterlogging, which threaten the productivity of these fields and the world’s food supply. Surprisingly, little ecological data on agricultural soils have been collected to understand and address these problems. How, then, can expanding and intensifying modern irrigation systems remain agriculturally productive for the long-term?

Archaeological case studies can provide critical insight into how irrigated agricultural systems may be sustainable for hundreds, if not thousands, of years. Irrigation systems in Mesopotamia, for example, have been cited consistently as a cautionary tale of the relationship between mismanaged irrigation systems and the collapse of civilizations, but little data expressly link how and why irrigation failed in the past. This dissertation presents much needed ecological data from two different regions of the world – the Phoenix Basin in southern Arizona and the Pampa de Chaparrí on the north coast of Peru – to explore how agricultural soils were affected by long-term irrigation in a variety of social and economic contexts, including the longevity and intensification of irrigation agriculture.

Data from soils in prehispanic and historic agricultural fields indicate that despite long-lived and intensive irrigation farming, farmers in both regions created strategies to sustain large populations with irrigation agriculture for hundreds of years. In the Phoenix

Basin, Hohokam and O’odham farmers relied on sedimentation from irrigation water to add necessary fine sediments and nutrients to otherwise poor desert soils. Similarly, on the Pampa, farmers relied on sedimentation in localized contexts, but also constructed fields with ridges and furrows to draw detrimental salts away from planting surfaces in the furrows on onto the ridges. These case studies are then compared to failing modern and ancient irrigated systems across the world to understand how the centralization of management may affect the long-term sustainability of irrigation agriculture.

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Chapter 1

INTRODUCTION: THE CHALLENGES OF SUSTAINABLE LONG-TERM IRRIGATION

Irrigated agriculture has been extolled as critical for meeting increasing food demand as our world's population rapidly approaches 8 billion people (FAO 2011). The Food and Agriculture Organization (FAO) estimates that 60 percent more food will be required to meet these demands and will have to come from irrigated agriculture (FAO 2003). The International Commission on Irrigation and Drainage (ICID 2012) agrees with this assessment and estimates that, in order to support the growing population, agricultural production will have to double within the next 25 years and that this doubling will likely have to come from irrigation agriculture. In fact, the predicted reliance on irrigation agriculture has resulted in the creation of a new slogan for the ICID: "more crop per drop" (FAO 2003). Indeed, the world's irrigated acreage has more than doubled over the past 50 years, while at the same time the cultivated acreage per person declined to less than 0.25 hectares, indicating that irrigation agriculture is both intensifying in current fields and expanding to new areas (FAO 2011).

Despite the expectations for the future role of irrigation agriculture, wide-ranging problems, both social and ecological, need to be addressed in order to maintain production of crops in modern irrigated fields for the long-term. Concerns about agricultural productivity in these irrigated fields include water availability, water quality, water access, salinization, groundwater depletion, and decreasing soil fertility (FAO 2011). In a recent assessment of global irrigated resources, the FAO estimates that 34 million hectares (or, 11% of the total irrigated global area of 301 million hectares) is affected by salinity problems, mostly in Pakistan, the United States, China, and India. A further 60-80 million hectares are plagued by waterlogging and associated salinization (FAO 2011). These numbers indicate that *over a third* of our irrigated acreage is under threat of serious ecological degradation.

Importantly, soils in these arid environments, like the case studies addressed in this dissertation - Phoenix Basin and coastal Peru, are highly vulnerable to degradation and frequently need strategies to maintain agricultural production over the long-term. In the U.S. Southwest, numerous studies of prehistoric rainfed fields have shown that frequent movement of people to new fields and fallowing is needed in order to maintain soil fertility (e.g., Kruse-Peeples 2013; Sandor et al. 2007). Similar studies in Peru (albeit the Andes, and not the coast) show that investment into terracing has allowed for the improvement of soil quality over 1500 years of agricultural use (Sandor and Eash 1995). Unfortunately, little research on the sustainability of long-term irrigated agricultural fields has been done. Archaeological and historical studies of the irrigation systems can offer essential insights concerning the long-term impacts of various irrigation practices that can inform the decisions made today about irrigation agriculture and soil management.

In addition to the need for maintaining production over the long-term, modern irrigation agriculture is intensifying to meet the demands of the global population, so it is important to recognize the implications of this process on soil quality, as well. The *intensification of agriculture* is defined as any attempt to add more labor to a field in order to increase agricultural production in a given field area. Strategies to intensify agriculture include terracing, multicropping, the addition of fertilizer, and, most importantly for this research, the construction of infrastructure, like irrigation canals (Boserup 1965; Erickson 2006; Netting et al. 1989). The intensification of agriculture has important implications for the quality of agricultural soils, since nutrients can be quickly extracted from soils as production increases, leaving fields degraded of essential nutrients for plant growth (Amiel et al. 1986; Cassman 1999; Matson et al. 1997; McAuliffe et al. 2001; McLauchlan 2007; Meyer et al. 2007; Reitz and Haynes 2003; Weil et al. 1993). Archaeological and ethnographic research, however, has shown that in some cases, farmers can effectively manage soil quality while intensifying production in their fields (Glaser and Woods 2004; Kirch et al. 2005; Leach and Fairhead 2000; Lehmann 2003; Netting et al. 1989; Netting 1993).

Moreover, irrigation systems require the cooperation of hundreds, if not thousands, of people over the distribution of a common pool resource – water – so researchers have also stressed the need for understanding the social contexts to maintain productivity in large-scale irrigation systems (e.g., Alauddin and Quiggin 2008; Wichelns and Oster 2006). Here, a *large-scale irrigation system* is defined as an agricultural system in which irrigation water is distributed over multiple communities and villages, indicating that cooperation or control over water occurs on a level higher than the household. Because the distribution of water can involve many households, communities, states, and countries, the social solutions to maintaining productivity in large-scale irrigated systems can be complex. For example, the distribution of water from the Colorado River has been subject to much debate, since multiple states (Colorado, Arizona, California, and Nevada) and countries (the United States and Mexico) are involved in the management and distribution of its water, resulting in many interstate and international agreements. In fact, one of the case studies of focus for this dissertation – the Gila River Indian Community – was recently awarded 311,800 acre-feet per year from the Colorado River, jeopardizing the future of irrigation agriculture for farmers with junior rights to water (DeJong 2007). Because of this complexity in stakeholder rights to water, sustainability scientists have honed in on the importance of social solutions to the management of these large-scale common resources, in addition to the ecological solutions to salinization and waterlogging.

Due to the level of cooperation or control needed to manage the distribution of water throughout an irrigation system, a major debate in the sustainability literature regarding irrigation has taken shape, resulting in a dichotomous approach to managing these systems: centralized, top-down management or bottom-up, community-based management. Here, the degree of the *centralization of management*, defined as the extent to which decision-making is concentrated in the hands of few people (usually elites), may be key in understanding the longevity of irrigation systems. For example, in a top-down system, state-level bureaucrats or elite classes hand down decisions to individual households and farms regarding irrigation water. In a bottom-up system, however, decisions regarding the distribution of water are handled at the scale of the community or individual canal systems. Research in modern irrigation systems has shown that these two management strategies can have wide-reaching effects on the sustainability of an irrigation system (e.g., see Lansing 1991 for a prime example from Bali where a bottom-up system transitioned to a top-down system). Chapter 7 provides an assessment of how the centralization of management may be related to the sustainability of the irrigated systems in the case studies addressed in this dissertation.

For these reasons, research on the long-term sustainability of irrigation agriculture has become especially pressing in recent decades. The dialogue concerning the sustainability of irrigated systems has focused mostly on ecological solutions to preventing or fixing salinized fields, such as frequent soil testing (e.g., Beare et al. 1997) or flushing of salts (e.g., Qadir et al. 2000). Direct ecological data on soils in irrigated fields, however, is rare, and studies infrequently link their limited ecological data to social and economic contexts under which irrigation operates, including the longevity and intensification of irrigation systems. Because people are intensifying modern irrigation agriculture that needs to persist for the long-term, understanding how these contexts variably affect the quality of soils is essential. I have designed this dissertation to address the ecological impacts of irrigation on soils under different social and economic contexts, including the longevity of irrigation and the intensification of irrigation, both of which are essential to supporting a growing global population for the foreseeable future.

Archaeology can provide a long-term view on the sustainability of large-scale irrigation systems, and the two case studies of focus for this dissertation – the Phoenix Basin and the north coast of Peru – can provide insight into the ecological effects of the longevity, intensification, and centralization of management of long-term irrigation in arid regions. For decades, archaeologists have assumed that the fragility of soils and uncertainty of water availability in arid environments across the world led to collapses of civilization and restricted the intensification of agriculture. For example, Mesopotamia has become a prime example of how improperly managed irrigation systems led to widespread salinization, waterlogging, and sedimentation, which has been associated with the collapse of major kingdoms in southern Mesopotamia (Gibson 1974; Jacobsen and Adams 1958; Rosen 1998; Weiss 1993). The people living in the regions of focus, however, seemed to avoid repeaated major collapses due to soil mismanagement. Did people employ strategies for long-term successful farming in different social and ecological contexts? If so what are the elements of these successful practices? For this dissertation, I examine two regions in which people irrigated their agricultural fields for centuries, indicating long-term success, and I assess impacts on soil quality in these ancient agricultural fields.

Introduction to the Case Studies of Focus – The Phoenix Basin and the North Coast of Peru

The archaeological remains of prehistoric and historic agriculturalists on the middle Gila River in southern Arizona and the Pampa de Chaparrí on the north coast of Peru provide excellent comparative case studies to explore the effects on soil quality of long-term irrigation agriculture in a variety of social and economic contexts (Figure 1.1). In addition to providing contexts that were farmed for centuries and intensified in different spatial and temporal contexts, these cases are two socially distinct “experiments” in intensified, long-term irrigation farming that allow me to assess how different irrigation management strategies may affect soil management in irrigated systems – one highly centralized management (coastal Peru) and the other community-based management (the middle Gila River) of the distribution of irrigation water. Using archaeological and ecological data, this interdisciplinary research documents and explains how agricultural intensity and longevity of irrigated systems affected the quality of the agricultural soils.

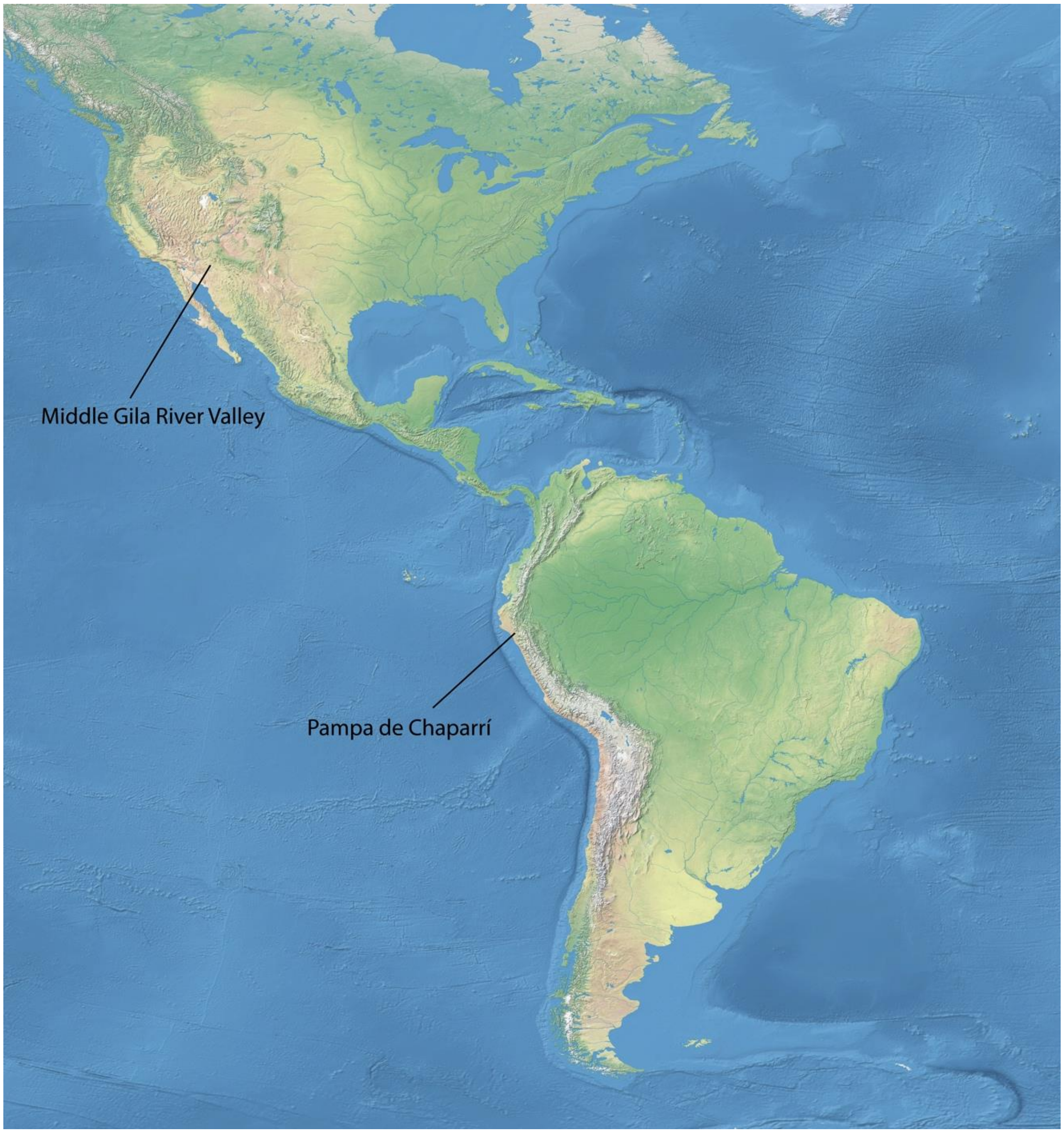


Figure 1.1: Map of the Two Case Studies of Focus: The Middle Gila River and the Pampa de Chaparrí on North Coast of Peru

Located in southern Arizona, the prehistoric Hohokam and the historic O'odham, descendants of the Hohokam, constructed large-scale irrigation systems throughout the Phoenix Basin to deliver water to their agricultural crops, mainly maize, cotton, beans, and squash. Their ancient agricultural fields provide a tremendous opportunity to not only study the social and ecological effects of the intensification of irrigation agriculture – with their transition from subsistence agriculture to a market economy - but also the impacts of long-term irrigation on soil quality – both infrequently studied in ancient examples. For over a millennium, Hohokam and O'odham farmers adapted to rapidly changing social and ecological contexts on the middle Gila River. The prehistoric Hohokam (AD 200 – 1450) faced changing streamflow (Graybill et al. 2006; Graybill and Nials 1989; Ingram 2010), possible immigration of outside groups into their territory (Lyons and Clark 2010), and changing political and social institutions (Abbott 2003) with economic and agricultural success. These social and ecological changes have been the subject of much archaeological research on how they may have affected the stability of Hohokam society. Like the Hohokam, their descendants, the historic O'odham (AD 1694 – 1950), faced similar challenges, but also adapted to incoming colonizing groups throughout the AD 1700 and 1800s. As Spanish and American groups entered southern Arizona, the O'odham rapidly changed their agricultural approaches to incorporate new crops and to enter new markets introduced by the colonizers (DeJong 2009). By comparing data from the subsistence-based Hohokam fields, farmed for over a millennium, to historic O'odham fields, farmed mainly for cash crop production, the effects on soil quality of both the longevity and the intensification of agriculture can be addressed.

Similarly, the prehispanic farmers on the Pampa de Chaparrí on the north coast of Peru constructed large-scale irrigation systems that fed their agricultural fields for over 600 years. Thousands of hectares of fields were constructed during the Sicán, Chimú, and Inka regimes (AD 900 – 1532) providing an excellent opportunity to study the effects on soil quality of long-term irrigation under centralized management of the distribution of water. The diversity of fields – both household and state-managed – on the Pampa also allows for the exploration of the ecological effects of the intensification of agriculture spatially. Some fields are enclosed by large adobe walls, and archaeologists argue that these walled fields were reserved for direct agricultural production by the state (Kolata 1990; Téllez and Hayashida 2004). Soil samples from these walled fields can be compared with fields that were unwalled, and likely managed at a less intensive level by the household (Netherly 1984).

The irrigation systems in both regions were used for centuries, if not a millennium, and provide an excellent opportunity to explore how long-term irrigation affected agricultural soil quality. The intensification of agriculture can also be explored in both regions, both temporally on the middle Gila River and spatially in the walled fields on the Pampa. Additionally, the irrigation systems in coastal Peru were constructed and managed by state-level bureaucracies, while the Hohokam and O’odham in the Phoenix Basin never reached this level of social complexity. With the benefit of this comparative analysis, the overarching research question to be addressed by this dissertation is: *What is* *the relationship between the longevity and intensification of irrigation agriculture and soil quality?* Soil samples were collected from a variety of contexts in both the Phoenix Basin and coastal Peru to address this question.

Introduction to the Research Themes

Building upon the question posed above, I address two research themes with the analyses of soil samples from ancient agricultural fields. These themes include clarifying (1) how long-term irrigation affected the quality of agricultural soils, and (2) how the intensification of agriculture affected the quality of soils. At a unique intersection of archaeological and modern agricultural research, this dissertation presents data and analyses from prehispanic and historic agricultural fields, focusing mostly on areas that the Gila River Indian Community (GRIC) and the Peruvian government have designated for future agricultural expansion. This work, then, is a document of past agricultural practices that enhances understanding of how different aspects of long-term irrigation agriculture affect soil quality to inform future agricultural expansion in both regions.

To undertake this research, a methodology was created to identify and sample ancient agricultural fields. While the Hohokam and O’odham irrigation systems have been intensively studied through the highly visible canals in the archaeological record, the adjacent agricultural fields that received that water have been largely ignored. The creation of the GRIC reservation prevented urbanization along the middle Gila and protected buried agricultural fields. In coastal Peru, the Pampa was abandoned shortly after Spanish conquest with little occupation since, preserving fields that remain visible on the surface. These buried agricultural strata and surface fields provide a wealth of information that can be sampled to clarify the impacts of long-term irrigation and the intensification of agriculture on soil quality in two irrigation systems that were managed at different levels of centralization.

Research Theme 1: The Effects of Long-Term Irrigation on Soil Quality

Human behavior has left a wide range of legacies on soils across the world with both positive and negative effects on their productivity. Soils, then, provide an important source of data regarding human impacts on the environment. Soils also form the basis for agricultural productivity. Thus, soil quality is an important indicator for how different activities, such as the intensification of agriculture, long-term irrigation, or cash cropping, may have resulted in the degradation or improvement of soils. This research theme is designed to evaluate the impacts on soils from long-term irrigated agriculture.

Irrigation is necessary for agricultural production in many arid regions across the world, including Mesopotamia, the north coast of Peru, and portions of the U.S. Southwest. Numerous studies in all of these regions have documented and analyzed the highly visible irrigation canals, documenting social organization, field command area of the canals, and labor input into the canal system (e.g., Farrington 1977; Hayashida 2006; Howard 2006; Keatinge 1974; Moore 1991; Netherly 1984; Sherbondy 1987; Woodson 2010). These studies are valuable for understanding the relationship between the irrigation canals, the management and distribution of irrigation water, and the control of labor to construct and maintain irrigation canals.

None of these studies, however, has done extensive research on the agricultural fields where people cultivated their crops. Researchers have speculated on the effects on the agricultural soils of long-term irrigation (e.g., Ackerly 1988; Artzy and Hillel 1988; Jacobsen and Adams 1958), but they have relied on data that do not sample the agricultural soils themselves. Using proxy data, such as a shift to more salt-tolerant crops, archaeologists have argued that, in some cases like Mesopotamia, salinization would have been a major problem for farmers in the past (Jacobsen and Adams 1958).

The soils analyzed in the regions sampled in this dissertation, however, were farmed successfully for centuries. Despite interest in how long-term irrigation by the Hohokam and coastal Peruvians may have affected soil quality, only a few research studies have actually tested soils to address this question (see Nordt et al. 2004 and Sandor 2010 for exceptions). Fortunately, previous studies on the geomorphology and canal system development in both case study regions elucidate many aspects of soil development, enhancing our ability to isolate the human impacts on soil quality. For this dissertation, I build upon this previous research and add hundreds of samples and analyses to our understanding of soil quality along the middle Gila River and in coastal Peru. With the analysis of these soil samples, I argue that salinization and alkalization of fields were effectively managed for more than a millennium in both case study regions. Each case study incorporated strategies – sedimentation through irrigation water from canals along the middle Gila River and sedimentation and salt management through raised beds in coastal Peru – to maintain soil quality during centuries of use.

Research Theme 2: Agricultural Intensification and Soil Quality

Intensification of agriculture is observed in both case studies – spatially on the Pampa de Chaparrí and temporally on the middle Gila River. On the middle Gila River, the intensification of agriculture is measured temporally between prehistoric and historic fields. To clarify how the O'odham agricultural system changed during the historic period, I use historic and archaeological data on O'odham settlement patterns and agricultural yields to document the intensification of agriculture during the historic period (Chapter 3).

On the Pampa de Chaparrí, soils from different types of fields that were used at different intensities at the same time in the past can be compared to understand how the intensification of agriculture affected soil quality on the north coast of Peru. Walled fields on the north coast of Peru were more intensively used in the past than unwalled fields, as the state likely controlled agricultural production in these areas (Chapter 4). Evidence for the intensification of agriculture has been tightly linked to the development and maintenance elite classes in different parts of the world (e.g., the Tarascan Empire in Western Mexico, Fisher et al. 1999), so these walled fields were sampled and compared to unwalled fields to evaluate the intensification of agriculture on the Pampa de Chaparrí.

Because the intensification of agriculture involves incorporating different strategies to increase agricultural output from the same area of land, soils can be rapidly degraded as nutrients are more quickly extracted. If soils are managed properly, however, with the use of strategies to maintain soil quality, soils can be farmed intensively without degradation (Netting et al. 1989; Sandor and Eash 1995). By comparing soils from prehistoric and historic fields along the middle Gila River and from walled and unwalled fields on the Pampa, the effects of the intensification of agriculture on soil quality are evaluated. I argue that, on the middle Gila River, most indicators of soil quality show that the intensification of agriculture historically did not result in the degradation of soil. On the Pampa, however, intensively used walled fields show some evidence for degradation compared to unwalled, less intensively farming fields (Chapter 6).

Thoughts on the Relationship between the Centralization of Management and the Sustainability of Irrigation Systems

In addition to the ecological implications of long-term irrigation, the management and distribution of water in an irrigation system impacts soil quality and therefore the sustainability of the irrigation system. Anthropological literature has highlighted that the centralization of management – or the social scale at which decision-making occurs – is key to the longevity of irrigation systems (Erickson 2006; Hunt 1988; Lansing 1991). Both the middle Gila River, managed at the level of each individual canal system, and coastal Peru, managed at the state-level, can be compared to understand how the centralization of decision-making may affect soil quality and longevity in these farming systems. Data from were not expressly collected to address the relationship between soil quality and the centralization of management, but a discussion of how the centralization of management may be related to the longevity of these systems is warranted.

In Chapter 7, the soil results, presented in Chapter 6, are evaluated in the larger context of irrigated systems across the world. Especially focusing on ancient Mesopotamia, which has been subject of much discussion concerning the failure of long-term irrigation systems, the persistence of long-term irrigation systems is discussed in the context of how they are managed. In this chapter, I argue that ethnographic and archaeological case studies indicate that that bottom-up management, or less centralized decision-making, does indeed more often result in more long-lived irrigation systems. When decision-making is removed from those who know the system - that is, the farmers who have obtained the knowledge to incorporate strategies to maintain productivity in irrigated fields over the long-term – systems become less sustainable. This conclusion is especially important for highly centralized, modern systems, like the Colorado River, that is designed to provide water to millions of people in the future.

Significance of Research

This dissertation contributes significantly to multiple disciplines, including archaeology, agronomy, and ecology. First, I have designed the research to answer pressing questions concerning how the farmers along the middle Gila River and coastal Peru managed their soils over the long-term. These questions are important to both our understanding of the major social transformations in each region and their relationship to soil quality, and to documenting how long-term irrigation can affect soil quality, which is important to many people farming in arid environments today. The data presented in this dissertation represent the few assemblages of soils collected from ancient and long-term irrigated contexts. Thus, instead of relying on proxy data to interpret how soil quality changed in the past (as has been done in Mesopotamia, see Chapter 2), this dissertation provides data on the farmed soils themselves to provide information on the relationship between long-term irrigation and soil quality.

The sampling strategies presented in this dissertation also provide methodological advances to identify and sample soils from ancient agricultural fields. Both study areas are located on highly dynamic, alluvial landscapes that have been subject to numerous anthropogenic and natural forces that have altered landscape and soil characteristics. These natural and anthropogenic factors needed to be controlled for in order to isolate the impacts of irrigation on the soil (Chapter 5 and Chapter 8). Because this analysis represents one of the first studies on prehispanic agricultural fields in the Phoenix Basin and coastal Peru, this dissertation presents the unique methodologies created to successful sample ancient sediments from both regions.

In addition to the theoretical and methodological contributions of this research to archaeology and agronomy, this dissertation is poised to provide much needed data concerning the ecological impacts of both long-lived and intensifying irrigation systems. Because direct ecological data from irrigated agricultural fields is rare, these archaeological case studies can provide much-needed ecological data from irrigated fields that were farmed for hundreds of years and provide contexts in which agriculture intensified. Interpretations concerning how soils are affected by both the longevity and intensification of irrigation agriculture can greatly add to our understanding of how modern irrigation agriculture can be more sustainable.

Thus, this research has important implications for the future of agriculture in arid environments, especially southern Arizona. Over the past decade, state planners, farmers, water researchers, and water users have stressed the growing problem of water availability for agricultural fields in this region. How and should agriculture continue if water becomes increasingly scarce as climate changes and population grows in the Phoenix Basin? One outcome has become clear with these ongoing discussions. With current plans to introduce 311,800 acre-feet of water annually to their agricultural fields due to the water settlement in 2004 (DeJong 2007), the Gila River Indian Community will have a great deal of influence on the future of agriculture and water in Arizona. If agriculture is destined to intensify and expand on the GRIC, what, then, does the intensification of land use mean for the long-term sustainability of farming on the GRIC? This future begs for further archaeological research of the past, and this dissertation provides much needed data to clarify how the expansion of irrigated agriculture affects soils and the cultivation of crops.

Dissertation Organization

The following chapters present the results of interdisciplinary field and laboratory analysis of soils from prehistoric and historic agricultural fields along the middle Gila River and on the north coast of Peru. Chapter 2 provides the theoretical background on the hypotheses tested in this dissertation. In this chapter, I discuss previous research on the intensification of agriculture and long-term irrigation systems. I also provide data on how soils have been analyzed in the contexts of these factors. Chapter 3 then covers the cultural and agricultural history of the first case study region – the middle Gila River. I argue in this chapter that the prehistoric Hohokam largely practiced subsistence agriculture, growing food for their own consumption and to barter for some goods, like cotton and pottery. During the historic period, O’odham subsistence farmers intensified agricultural production as they transitioned to a market economy. Chapter 4 provides the cultural and environmental history of the Pampa de Chaparrí on the north coast of Peru and background on the prehispanic irrigated agricultural system. Here, I provide evidence that many irrigation canals were managed at a more centralized level than those in the

Phoenix Basin and describe the diversity of fields on the Pampa, including the walled fields, which were likely controlled by the state for agricultural production.

Chapter 5 describes the methods used to identify and sample agricultural fields and to process and analyze soil samples. This chapter presents the unique approaches used to study surface and buried ancient agricultural fields – something rarely done in prehistoric and historic contexts in coastal Peru and the Phoenix Basin. It also provides an in depth description of the analyses performed on soil samples to understand the relationship between the various social contexts of interest in this dissertation and soil quality. Chapter 6 presents the results of the analysis of soils from ancient agricultural fields to address the two research themes. In this chapter, I argue that while soils were effectively managed over the long-term in both the Phoenix Basin and coastal Peru, important differences emerge between the case studies when the intensification of agriculture is considered. Next, in light of the conclusions research from the soil analyses presented in Chapter 6, Chapter 7 evaluates how the management of the irrigation system may be related to the longevity of the irrigation system, by expanding the analysis to other parts of the world, including southern Mesopotamia. Finally, Chapter 8 concludes this dissertation with an assessment of how research in ancient irrigated systems can be improved in the future and provides necessary considerations for sampling in these agricultural systems.

Chapter 2

SOILS AND THE LONGEVITY AND INTENSIFICATION OF LONG-TERM IRRIGATION AGRICULTURE

To address the main question of this dissertation - *What is the relationship between the longevity and intensification of irrigation agriculture and soil quality?* - hundreds of soil samples from the middle Gila River in southern Arizona and the Pampa de Chaparrí on the north coast Peru were collected from ancient irrigated agricultural fields. The large number of samples represents one of the few assemblages of soils from irrigated agricultural fields in the world, and the sampling methodology created for this dissertation allows for diachronic and spatial analysis of the intensification of agriculture to assess whether long-term irrigation resulted in the degradation or enhancement of agricultural soils.

In this chapter, I introduce the theoretical underpinnings of the two themes developed in this dissertation: (1) the effects of the *longevity* of irrigation on the quality of agricultural soils, and (2) the effects of the *intensification* of irrigation agriculture on soil quality. Here, ***soil quality*** is defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (NRCS 2013). While soil quality can be a controversial measure (e.g., Sojka et al. 2003), it was chosen since this dissertation is designed to see how soils were degraded or enhanced for the purpose of irrigated agricultural production. Thus, soil characteristics are defined as degraded or enhanced based on their importance to agricultural crop growth. I also briefly introduce the methods and sources of data that are used to address each research theme. These methods are explained in greater detail in Chapter 5.

Research Themes for this Dissertation

Research Theme 1: Determining the Effects of Long-Term Irrigation on Soil Quality in Arid Environments

Arid environments are typically viewed as marginal for agricultural production, but innovative agricultural strategies, like irrigation, have allowed for surplus food production in many parts of the world, including the U.S. Southwest, coastal Peru, and Mesopotamia (Scarborough 2003). *How, then, might long-term irrigation in arid settings affect the quality of agriculural soils?* In the following sections, I provide information on how irrigation may lead to the enhancement or degradation of agricultural soils. Based primarily on studies of the ecology of irrigation farming and indirect indicators of soil quality, irrigation can quickly degrade soils through salinization or the removal of nutrients through crop production, but soil quality can be maintained, if strategies, like sedimentation or leaching of soils, are implemented.

Soil Quality and Long-Term Irrigation. Surprisingly, the effects of long-term irrigation have been infrequently studied in the context of ancient irrigation systems, leading to little understanding of how soils have been affected by hundreds of years of irrigated farming. Due to the negative effects of irrigation on modern fields, many researchers have assumed that intensive irrigation, especially after hundreds of years, would have led to the degradation of soils in these ancient fields (Ackerly 1988; Dart

1986; Jacobsen and Adams 1958). While numerous studies have used proxy sources of data to infer effects of irrigation on soil (e.g., historic documents noting a shift to more salt-tolerant crops), very few studies sample the agricultural soils themselves (Sandor and Homburg 2010). With this uncertainty in how soil quality is affected by long-term irrigation, more research on the agricultural soils themselves is needed to clarify the relationship between long-term irrigation and soil quality.

Ecological studies of modern irrigation fields can help clarify the effects that irrigation has on soil quality, although the long-term effects of irrigation cannot be discerned from these short-term studies. Irrigated soils face a number of threats to soil health that lead to decreased crop production, including salinization (El-Ashry 1985; Proust 2008; Scarborough 2003), alkalization (DeJong 2011; Marlet et al. 1998; Southworth 1919; Wopereis and Ceuppens 1998), and excessive sedimentation of agricultural fields (Jacobsen and Adams 1958; Huckleberry 1992; Ong and Orego 2002). Studies of industrial irrigation agriculture in Mesopotamia, Australia, and the Western United States have documented these problems in modern fields (e.g., Proust 2008).

Salinization and Alkalization. One of the biggest threats to irrigated soils (or, perhaps the threat that is most discussed in scientific literature) is salinization. Salinization, or the accumulation of salts in the soil, has been extensively discussed in the context of long-term irrigation. While many modern irrigated agricultural fields display signs of extensive salinization (Butler and von Guerard 1996; Proust 2008), little is known about the effects of long-term irrigation on the salt content in agricultural soils.

The ions responsible for salinization are: Na^+, K^+, Ca^{2+}, Mg^{2+} and Cl^-, all of which represent different types of salts that can accumulate in the soils (Brady and Weil 2008; FAO 1988; Umali and Deininger 1993). While these ions are beneficial to the productivity of agricultural crops, sodium cations in excessive amounts prevent plants from uptaking water from the soil. Some crops that are especially sensitive to salt buildup in the soil are beans, wheat, and corn, while barley and cotton are more tolerant of salt in the soil (Francois and Maas 1994; Maas and Hoffman 1977).

While salinization can occur from a variety of natural processes, such as mineral weathering, irrigation is the cause of anthropogenically-driven salinization of agricultural fields (FAO 1988). The accumulation of salt in the soil can occur in two different ways: by increasing the level of the water table resulting in capillary movement of salts to the top of the soil profile (Figure 2.1) or by allowing irrigation water high in salt content on the surface to evaporate onto the fields (Figure 2.2), both of which occur from the improper use of irrigation on water agricultural fields.

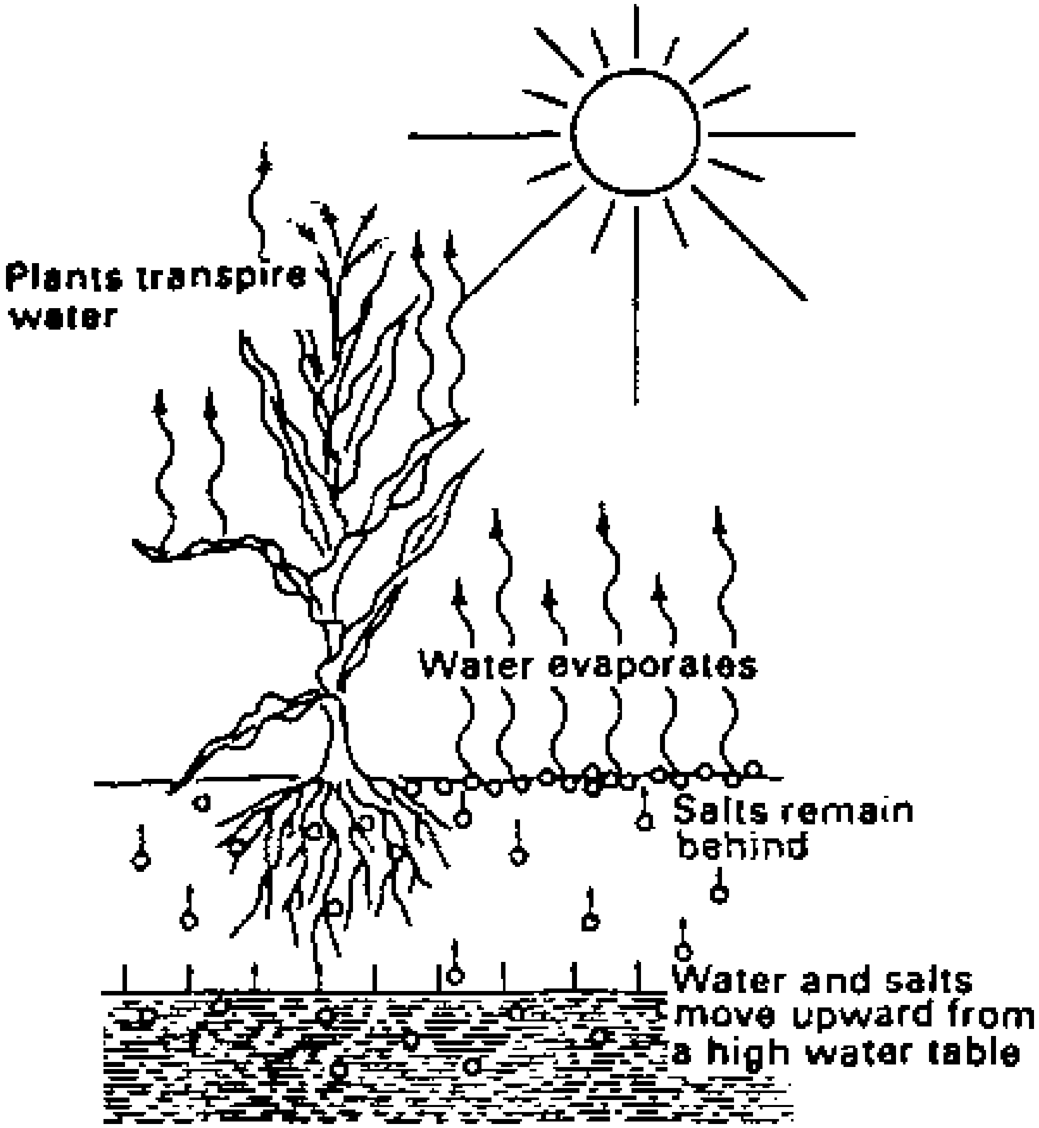


Figure 2.1: Salinization due to an artificially high water table (courtesy of the FAO 1988)

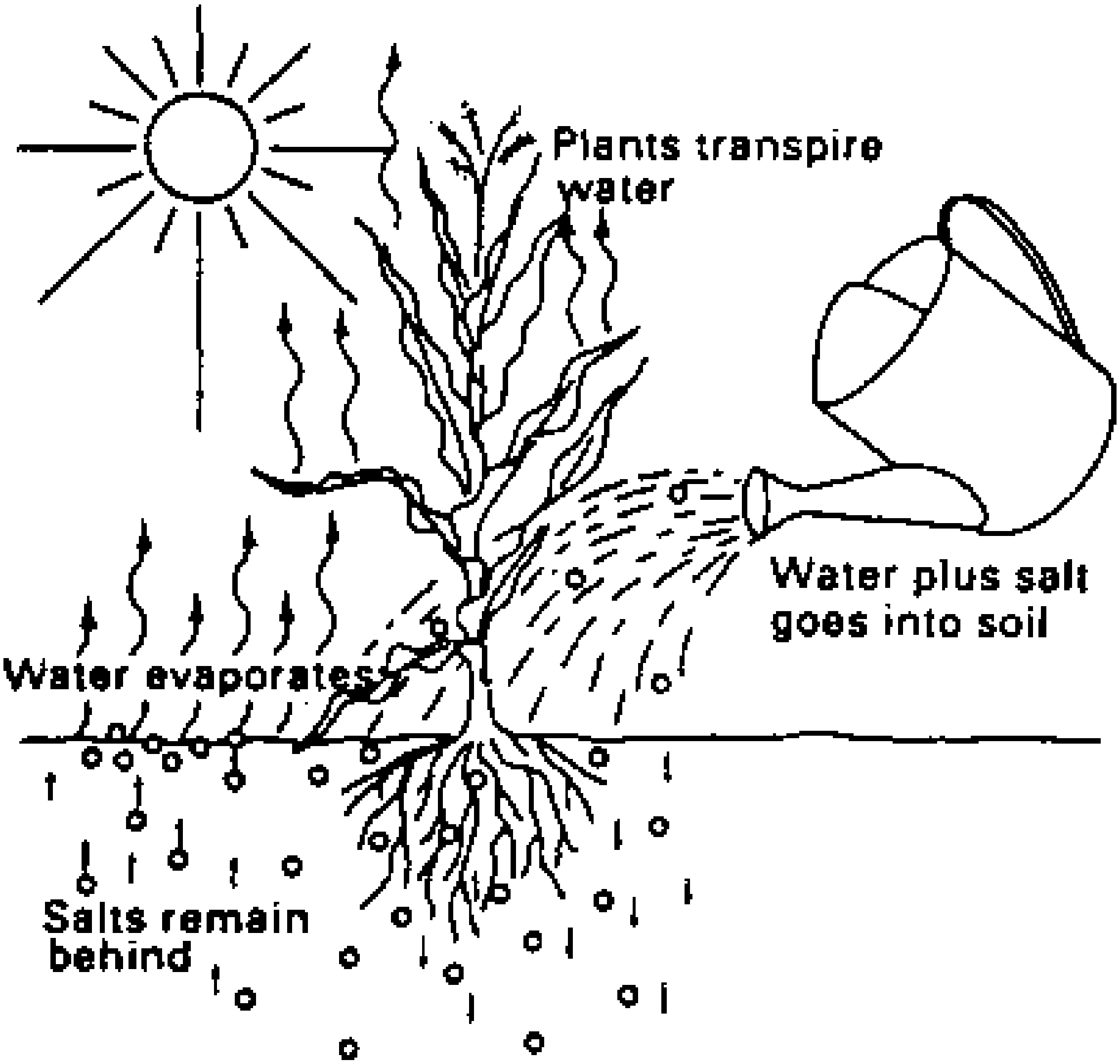


Figure 2.2: Salinization due to Excessive Irrigation (Courtesy of the FAO 1988)

Salinization has been much discussed with regard to ancient irrigated systems, especially those in Mesopotamia. Extensive historic sources document the production of crops, the planning of communal architecture and houses with regard to soil stability, and the quality of soil. These historic documents from southern and central Mesopotamia indicate problems of salinization and sedimentation during three separate occasions, one from 2100 -1700 BC, another from 1300 – 900 BC, and a short period after AD 1200 (Artzy and Hillel 1988; Jacobsen and Adams 1958). Some scholars suggest, however, that ancient Mesopotamians would have had strategies in place to combat salinization, through frequently flushing of the soils, since these strategies, like fallowing, are discussed in historic documents (Altaweel and Watanabe 2011; Powell 1985). While studies on ancient irrigated soils have not been done in Mesopotamia, archaeologists infer salinization from clues in historic documents, including the shift from wheat to the more salt-tolerant barley, the mention of saline soils by temple architects, and reduced crop yields due to declining soil fertility. Others argue that these historic documents do not accurately portray the evidence for salinization during these time periods (Powell and Kalb 1985). Additionally, archaeological and modern evidence point to the naturally high salinity levels of southern Mesopotamian soils, so salinization may have been an ongoing process that needed to be addressed continuously (Dileman et al. 1977; Hardan 1971). Regardless, soil sampling on these ancient agricultural fields is needed to clarify whether salinization was a problem for Mesopotamian agriculturalists in the past.

Some limited soil sampling has been performed on prehispanic soils on the north coast of Peru, where another large-scale irrigation system was constructed and used for thousands of years (Nordt et al. 2004). Nordt and colleagues (2004) found that while the naturally coarse texture of the soil helped to prevent the buildup of salts in the soil, the low levels of total nitrogen in the soil would have necessitated inputs to maintain crop productivity for hundreds of years.

In the Phoenix Basin, salinization has been hypothesized as a possible factor in the Hohokam collapse in the mid AD 1400s (Ackerly 1988; Bayman et al. 1997; Dart 1986; Haury 1976; Krech 1999; Palacios-Fest 1994). These studies, like those from Mesopotamia, rely on proxy data to argue that salinization did or did not occur. Haury (1976) praises the ability of Hohokam farmers to maintain soil quality over thousands of years, and Ackerly (1988) argues that the longevity of Hohokam farming indicates that salinization was not a problem. Krech (1999), however, critiques the approach that archaeologists have used in the past to address salinization in the Hohokam case study in his book *The Ecological Indian*. He argues that archaeologists and anthropologists have "nobilized" the Hohokam's ability to properly manage their environment and that these stereotypes of a Hohokam farmer living in harmony with nature have not allowed for hypotheses concerning salinization to be properly addressed. Using historic data on alkaline lands documented by O'odham farmers on the middle Gila River, Krech argues that salinization may have indeed been a major problem for the Hohokam. Krech, however, does not recognize the unique environmental circumstances that plagued O'odham farmers during the late AD 1800s and early AD 1900s - the loss of water on the Gila, leading to the inability to flush salts from agricultural fields that would have exacerbated salt buildup in the agricultural fields (DeJong 2011).

Many ethnographic and modern case studies of irrigated fields also indicate that salinization only becomes a problem when water shortages loom, reducing the ability of farmers to leach salts from the soils by flooding their fields (Altaweel and Watanabe 2011; Castetter and Bell 1942; DeJong 2011; Jacobsen and Adams 1958; Powell and

Kalb 1985; Southworth 1919). Furthermore, salinity levels of the water being added to the fields are more concentrated in times of low streamflow (Butler and von Guerard 1996). Thus, salinization may have become a problem for these ancient societies in times of low water flow to the fields, exacerbating the problem of low water availability to crops and the inability to flush salts from the soil.

Another effect of irrigation agriculture can be the accumulation of sodium – a specific type of salt - in the soil, leading to alkalinity – an issue that O'odham farmers frequently mentioned as a problem in the late AD 1800s and early AD 1900s on the middle Gila River (Southworth 1919). With the accumulation of the Na^+, the specific ion for sodium, soils can become sodic (also referred to as alkaline), which chemically affects crops and degrades soil structure, leading to poor water infiltration and water availability for plants. Interestingly, alkalization has been largely ignored in literature concerning ancient agricultural fields (or frequently lumped together with salinization), but due to the prevalence of this problem along the middle Gila River in the ethnographic literature, alkalization is of particular interest for this case study region.

Sedimentation. Sedimentation is another effect of long-term irrigation, resulting in both positive and negative consequences for soil quality. While irrigation canals are built primarily to deliver water to agricultural fields in arid environments, these canals also carry suspended sediments in the water, which are deposited in the canals and on agricultural fields when the water slows to a point that its velocity can no longer carry its suspended load. This sedimentation has been shown to have beneficial effects on the soil, by adding fine sediments and organic matter to otherwise coarse arid soils (Castetter and

Bell 1942; Doolittle 2000; Huckleberry 1992; Russell 1908; Sandor 2006; Schaafsma and Briggs 2007). However, excessive sedimentation can lead to the destruction of crops and canal systems, inhibition of soil aeration and infiltration, and constant dredging in order to maintain water flow through canals. If excessive sedimentation occurs, usually due to uncontrolled flooding, canal head gates may need to be moved in order to maintain appropriate slope for movement of water or crops may need to be replanted if seedlings are buried by the sediment (Dart 1986; Trout 1996).

Some ancient case studies have documented problems with sedimentation in agricultural fields. Those who have documented salinization of Mesopotamian soils have also observed varying degrees of sedimentation in the region, with as much as 10 meters of silt accumulating over 5,000 years from both natural and anthropogenic sources (Jacobsen and Adams 1958). These sedimentation rates have been shown to lead to the abandonment of extensive canal and settlement systems. Sedimentation from overbank flooding from rivers and canals and from excessive irrigation has also been documented in limited case studies in northern and southern Peru. Huckleberry (2008) briefly mentions the presence of a buried anthropogenic deposit on the Pampa de Chaparrí on the north coast of Peru – the region of focus for this dissertation. Hesse and Baade have also identified anthropogenic layers 4 meters thick in southern Peru representing what they call "a geoarchive which holds information on the history of irrigation agriculture as well as information on possible natural disturbance by extreme fluvial events" (2009:119).

In the greater Hohokam area, researchers have studied the legacy effects of long-term irrigation and dry farming along Cave Creek, north of the Salt River (Hall et al.

2013; Schaafsma and Briggs 2007). Schaafsma and Briggs (2007) argue that prehistoric Hohokam famers along Cave Creek diverted water from the creek with canals and then, using a series of terraces and check dams, reduced the flow of water causing it to drop fine sediments (predominantly silt) onto the agricultural fields. Huckleberry (2011) explores the intentionality of this sediment deposition by Hohokam farming and agrees this anthropogenic buildup of soils was likely the result of intentional diversions of water rich in sediment to the agricultural fields. Huckleberry (1992) has also documented sedimentation rates of 0.5 to 2.0 mm per year as a result of overbank flooding of irrigation canals in the Queen Creek and Salt River areas. In these cases, it appears that sedimentation in controlled amounts was beneficial to agricultural production.

These studies demonstrate the association of sedimentation and long-term irrigation in some areas of the Phoenix Basin and coastal Peru (Baade et al. 2008; Dart 1986; Hall et al. 2013; Hesse and Baade 2009; Huckleberry 1992, 2011; Means 1901; Schaafsma and Briggs 2007). Only a few samples, though, have been tested for salt and sodium content, and the naturally high salt content in unfarmed soils makes interpretation of the anthropogenic addition of salts difficult (Miles 2013; Sandor 2010). Thus, our understanding of how long-term irrigation on the middle Gila River and coastal Peru affected soils over the long-term, whether through salinization, alkalization, and sedimentation, is still in its infancy.

Soils and Long-Term Agriculture in the Prehispanic U.S. Southwest and Peru. Because of the lack of research on ancient irrigated systems, studies on ancient dryland fields may clarify how long-term agriculture degrades or enhances soils. Many studies of prehistorically cultivated soils across the U.S. Southwest have shown that some fields have been depleted of essential nutrients for crop growth, and in other cases unaffected, by prehistoric cultivation (Dominguez and Kolm 2005; Doolittle 1985; Doolittle 2006; Homburg et al. 2005; Homburg and Sandor 1997; Sandor and Gersper 1988; Sandor et al. 2007; Schaafsma and Briggs 2007; Sullivan 2000). For example, Sullivan (2000) argues that total phosphorus was lower in cultivated Mollisols, while the Aridisol soils show no decreased fertility due to long-term agriculture in terraces by the Grand Canyon in northern Arizona. These results reflect those found by Sandor and Gersper (1988) in their investigation of Mollisols in southwestern New Mexico, which also exhibit lower phosphorus and organic matter in prehistorically cultivated soils. In fact, in their greenhouse study, they show that agricultural productivity in this region would have benefitted greatly from nutrient inputs.

Other research in prehistorically dry-farmed fields show that strategies, like placing fields in runoff catchment areas or fallowing, can be implemented in fields across the U.S. Southwest to enhance or maintain soil quality. In these agricultural fields, prehispanic farmers constructed infrastructure, such as rock grids, terraces, or mulched fields, in order to capture water and nutrients, decrease evaporation, and increase water infiltration in the soil (Homburg et al. 2005; Kruse-Peeples 2013; Lightfoot 1996; Doolittle et al. 2004; Sandor et al. 2007). These agricultural strategies helped to maintain or enhance soil quality under long-term agriculture.

For example, in northern New Mexico, Lightfoot (1994) demonstrates the benefits of adding rocks to fields, which provided a mulching effect on these otherwise arid soils and maintained water availability to crops. Mulched grids in the Safford region in southeastern Arizona exhibit higher levels of nitrogen and available phosphorus than uncultivated soils (Homburg et al. 2004). Extensive research performed on traditional agricultural fields on the Zuni Reservation has also shown how farmers took advantage of alluvial fans that received runoff from precipitation, concentrating water onto the agricultural fields. Archaeological and agronomic studies have indicated that indigenous farmers constructed and maintained a complex system of soil nutrient recharge by placing fields where runoff from fertile, upland soils can bring organic rich sediments and water, also referred to as "tree soil," to the fields in order to make them more productive (Homburg et al. 2005; Norton et al. 2007; Sandor et al. 2007).

Kruse-Peeples' (2013) research in central Arizona models how nutrients enter and leave the agricultural fields in their dryland environment to understand how runoff from precipitation may increase soil quality in prehistoric agricultural fields. While Sandor and colleagues' research showed that runoff was key to maintaining fertility, Kruse-Peeples found that frequent fallowing was necessary in order to maintain agricultural productivity for the 150 years these fields were likely in use. Additionally, Nakase (2012) has demonstrated that eolian inputs from blowing dust are key driver of soil fertility in the region.

Little research has been done on agricultural soils in coastal Peru and the Andes, but the research shows again that strategies can be used to maintain soil quality for millennia. Sandor and Eash (1995) and Goodman-Elgar (2008) provide soils data from large-scale irrigated terraces in the Colca and Paca Valleys in the Peruvian Andes. These terraces have been cultivated continuously for over 1500 years, indicating their long-term sustainability. They show that the investment and maintenance in the infrastructure of the terrace system was necessary to maintain production for so long. These terraces prevent erosion on steep slopes, increase A horizon thickness, and maintain levels of organic carbon and available phosphorus. These terraces are so productive that Sandor and Eash (1995) hypothesize that the elevated levels of phosphorus may be due to the historically documented (and likely prehistorically practiced) application of seabird guano or camelid dung to the fields. Thus, in the one Peruvian case study from an archaeological context, the investment into and maintenance of the terraces and the application of guano were key in maintaining soil productivity.

All of these examples support the assessment that soils in these regions are vulnerable to degradation if farmed for a long period of time. Farmers in many of these cases, however, incorporated effective strategies, such as stone mulching and terracing, to maintain soil quality over the long term in their agricultural fields. If these strategies were not implemented, it is likely that soils would have degraded quickly, as they did in the southwestern New Mexico.

Assessing Research Theme 1: How Did the Longevity of Irrigation Affect Agricultural Soil Quality? These studies of both modern and prehistoric agricultural systems have shown that soil characteristics important to agricultural productivity are affected differentially over the long term in irrigated agricultural fields (Cassman 1999; Doolittle 2003; Homburg et al. 2005; Matson et al. 1997; McAuliffe et al. 2001; McLauchlan 2007; Meyer et al. 2007; Sandor and Gersper 1988; Sandor et al. 2007).

Degradation is seen in a reduction in nitrogen, phosphorus and other nutrients essential for crop growth, excessive sedimentation, salinization, and lower production of biomass centuries after the abandonment of the fields, indicating decreased soil quality (Holliday 2004; Homburg and Sandor 1997; Homburg et al. 2005; Sandor et al. 1990; Sandor and Gersper 1988; Schaafsma and Briggs 2007). Enhancement includes the addition of organic matter and nutrients to the soil that may increase agricultural productivity. Given that the long-term effects of irrigation on soil properties vary, further research is necessary to clarify the consequences of long-term irrigation from centuries of agricultural use in the Phoenix Basin and the north coast of Peru.

To do so, over 500 soil samples have been collected, tested, and analyzed from prehispanic and historic agricultural fields on the middle Gila River and the north coast of Peru, farmed for hundreds of years. Analyses of soil characteristics linked to longevity of farming include electrical conductivity (salinity), sodium adsorption ratio (alkalinity), nitrogen, available phosphorus, soil texture, pH, and organic carbon. These soil characteristics provide insight into whether long-term irrigation enhanced or degraded agricultural soils. Additionally, data on the characteristics of the irrigated soil, including width, depth, and color of the agricultural field, were collected during fieldwork to further understand how these soils were affected by irrigation.

Research Theme 2: Determining the Effects of the Intensification of Irrigation Agriculture on Soil Quality

The intensification of agriculture is a well-documented process in modern and ancient case studies and is currently occurring in irrigated fields today. Many modern agricultural fields show signs of serious soil degradation, but some ethnographic research indicates how the additional labor input can lead to soil enhancement. *How, then, might the intensification of irrigation enhance or degrade agricultural soils in the two ancient case studies studied in this dissertation?* To address this question, I first provide the theoretical background for defining and measuring the intensification of agriculture in ethnographic and archaeological cases. I then show how the intensification of agriculture has both degraded and maintained soil quality in a variety of case studies from around the world.

The intensification of agriculture occurred over time in the middle Gila case, but is evident spatially in the Peru case. On the middle Gila River, O'odham farmers intensified agriculture throughout the historic period to meet the demands of markets being introduced by Spanish and American colonizers who relied on the O'odham for food. Thus, soils from prehistoric (subsistence-focused) and historic (cash crop-focused) fields are compared to measure the effects of the intensification of agriculture in the Phoenix Basin. In contrast, on the north coast of Peru, soils from fields that were used at different intensities at the same time in the past are compared to understand the effects of the intensification of agriculture. Walled fields on the north coast of Peru are argued to have been used for more intensive, state-controlled agricultural production (Kolata 1990; Moseley and Day 1982; Téllez and Hayashida 2004). So, soils from walled fields and unwalled fields are compared to measure the effects of the intensification of agriculture for this case study.

With the Phoenix and Peru case studies, I argue that soils in arid environments are highly vulnerable to degradation with the intensification of agriculture, but if managed properly, these soils can be farmed for centuries, if not millennia. Management strategies that maintain soil quality in intensifying systems include fallowing, the addition of sediments and nutrients from runoff, and the construction of infrastructure that prevents soil erosion. Irrigated systems represent the most intensive form of agriculture in arid environments, so strategies to maintain soil quality were certainly needed in the past in order to ensure productivity for centuries.

Defining the Intensification of Agriculture and Identifying it in the Archaeological Record. Defining and analyzing the intensification of agriculture and the processes leading to it have been the subjects of much debate among anthropologists, geographers, and archaeologists since Ester Boserup's seminal book in 1965. Boserup (1965) defines intensification simply as the addition of more labor to a field in order to increase agricultural production. Strategies to intensify agriculture include decreased fallow times, investment in infrastructure (such as irrigation canals or terraces), multi- and intercropping, and adding inputs, like fertilizer, to increase agricultural production. Boserup attributes this process to increasing population density, resulting in the need for farmers to increase labor on their plot of land to produce more crops. With her book, Boserup provides a simple baseline toward a theory of the intensification of agriculture that can be built upon and applied to both modern and ancient societies.

Over the decades since her book was published, researchers have endeavored to refine and enhance this model of intensification with ethnographic and historic case studies. While Boserup added greatly to our understanding of agricultural use by providing a continuum of intensity of agricultural production (as opposed to simply cultivated or not cultivated), researchers have sought to improve her approach to fully reflect the complexity of the dimensions influencing agricultural decision-making and intensification (Brookfield 1972, 2001; Erickson 2006; Leach 1999; Morrison and Lycett 1994; Morrison 1996; Netting 1993). Various factors leading to the intensification of agriculture have been stressed, including technological innovation (Hunt 2000), a market economy (Brookfield 2001; Netting 1993), risk mediation strategies (Allen 2001; Wilk 1997), political economy (Fisher et al. 1999), and the maintenance of land tenure claims (Stone and Downum 1999) in prompting the intensification of agriculture, instead of simply focusing on the increase in population density as did Boserup (1965).

Brookfield (1972, 2001), for example, sees the Boserupian view of change as unilinear and simplistic. He argues that intensification can be defined not only through the increasing labor input into the landscape to increase production, but also through the diversification of strategies (i.e., incorporating dry farmed fields in conjunction with irrigated fields) and investment in agricultural infrastructure, like terraces, in order to mediate risk against food shortfall (2001:189). Erickson further highlights the factors of "… innovation, diffusion of technological improvements, competition, agency, market demands, historical contingency and culture," all of which may influence agricultural change and intensification (2006: 335). Furthermore, production must be *more intensive* than previous cultivation in order for intensification to have occurred (Morrison 1996). Stone and Downum (1999) further stress that the processes leading to intensification are highly dependent on local agroecological conditions and technological ability. These other factors leading to the intensification of agriculture are essential for the case studies of focus in this dissertation, since population density seems not to have been the main driver in decisions to intensify agriculture on the middle Gila River or the Pampa de Chaparrí (see below and Chapters 3 and 4).

Numerous case studies have shown that the intensification of agriculture occurs without increasing population density, especially in areas of ecological variability and unpredictability, like the Pacific Islands. Allen (2004), for example, contends that strategies typically argued to be indicators of the intensification of agriculture in the Kona area of Hawaii – stone mulching fields and crop diversification – were actually risk buffering strategies in AD 1450. These strategies were *not intended* to increase production or intensify agriculture, but to hedge risk in a risky environment, in which rainfall is unpredictable and the quality of soils varies across the island (Allen 2004; Vitousek et al. 2004). Thus, the intensification of agriculture likely occurred on this island due to efforts made to buffer against risk, not simply as a reaction to increasing population density.

Regardless of *why* agricultural intensification occurred, these studies demonstrate that agricultural intensification can be accurately observed and recorded in ancient cases with the presence of visible infrastructure, like irrigation canals. In Chapters 3 and 4, I document patterns of agricultural intensification in the archaeological and historical records on both the middle Gila and the north coast of Peru. On the middle Gila River, intensification occurred due to the historic transition to cash cropping, while on the north coast of Peru, intensified agricultural production was one part of the agricultural system, occurring within walled fields controlled by the state. The following sections provide theoretical background regarding the relationship between the intensification of agriculture and market economies and political economy, both of which inform the processes leading to the intensification on the middle Gila River and Pampa de Chaparrí, respectively.

Market Economies and the Intensification of Agriculture. The intensification of agriculture occurred on the middle Gila River during the historic period, as the O'odham focused on cash cropping for markets introduced by colonizers (Chapter 3). While not specifically cited as a driving factor in Boserup's theory of the intensification of agriculture, anthropologists have long cited the entrance to a market economy as a driving force leading to the intensification of agriculture (Netting 1989; Netting 1993; Stone et al. 1984). In a later publication, Boserup herself (1990) acknowledged that entering a market economy is a key factor leading subsistence agriculturalists to intensify agriculture.

Ethnographic and historic sources are replete with examples of how the agricultural strategies of subsistence farmers change when they enter a market economy, either voluntarily or not. These case studies show mixed responses from farmers, resulting in both success and failure, but almost always people alter their farming strategy either through the extensification and intensification of agriculture, depending on the availability of land, to increase production (Hutchinson et al. 1998; Netting et al. 1989; Netting 1993; Pavao-Zuckerman 2007; Pavao-Zuckerman and LaMotta 2007; Sheridan

2006; Spielmann et al. 1990; Spielmann et al. 2009; Stone et al. 1990; Tarcan 2005; Trigg 2003). If land is readily available, farmers produce more crops for the market by expanding their agricultural land use to areas that were not previously farmed.

In areas of high population density or limited available arable land, however, extensifying agriculture is not always possible (e.g., the Kofyar in Nigeria or Nepalese agriculturalists; Netting 1993; Schroeder 1985). In those cases, farmers often resort to intensifying agriculture in order to produce more crops for the market (see Netting 1993 for multiple examples). The Kofyar in Nigeria provide an excellent example of the intensification of agriculture while transitioning from subsistence agriculture to a market economy (Netting et al. 1989; Netting 1993; Stone et al. 1984). The Kofyar entered the market willingly, as the Nigerian government expanded transportation opportunities with the construction of new roads and provided access to growing markets. The Nigerian government, however, did not interfere with or regulate Kofyar agriculture, allowing the Kofyar to voluntarily increase production for cash cropping with their own agricultural strategies (Netting et al. 1989; Stone et al. 1984), similar to the O'odham on the middle Gila River.

With higher populations (being driven by a number of factors, including the influx of new people into the region) and the opportunity to sell crops, the Kofyar intensified agriculture and increased labor input into their fields to increase cash cropping (Netting et al. 1989). In order to increase labor, cooperative work among neighbors and friends expanded and households increased the number of children they had, allowing more intensive strategies of agriculture, including field ridging and multicropping. Stone and colleagues (1984) argue that access to a market played a significant role in this transition to cash cropping and the intensification of agriculture. Netting further explains the influence of a market economy, which adds to population pressure in the form of migration and land shortages close to places where a market is easily accessible. Netting (1993: 292) argues, "When land becomes scarce because of increasing immigration, natural population increase, or attraction of people to a market center, the desire to raise yields per unit area and the higher density of population will further the intensification process." Stone and colleagues (1984) and Netting (1993) argue that the market economy and higher population densities resulted in the intensification of agriculture and increased input of labor in their agricultural system, similar to what occurred on the middle Gila River historically (Chapter 3).

Political Economy and the Intensification of Agriculture. On the Pampa de Chaparrí, some fields were controlled by the state (walled fields) and others were not (unwalled fields). In early state-level societies, the intensification of agriculture was necessary to fund elites and bureaucracy (e.g., Boserup 1965; Brookfield 1972; Brookfield 2001; Childe 1950; Earle 2002). The rise of complexity and urbanism is frequently accompanied by an increased investment in technologies to intensify agricultural production to support growing population, expanding cities, developing elite classes, and increasing trade (Blanton et al. 1982; Boserup 1965; Brookfield 1972; 2001; Erickson 2006; Feinman et al. 1985; Fisher et al. 1999; McCoy and Graves 2010). It is clear from multiple studies across the world that political economy and agricultural production are intrinsically linked (Brumfiel and Earle 1987; Costin and Earle 1989;

D’Altroy et al. 1985). Fisher and others succinctly explain, “political-economy-based explanations assert that intensification is a response to socio-economic systems promoting predictable surplus to facilitate kin-based exchange, risk management, craft specialization, and lineage-based demands for tribute” (1999:644).

Numerous state-level societies in the past have been shown to exert considerable control over agriculture, in form of extracting taxes, requiring the obligation of labor, or taking over agricultural fields in total. This control has been documented in Mesopotamia (e.g., Adams 1978; Fall et al. 2002; Wilkinson et al. 2007), Mesoamerica (e.g., Fisher et al. 1999; Fisher 2005; Calnek 1972; Whitmore and Turner 1992), Peru (e.g., Farrington and Park 1978; Hastorf 2009), Hawaii (e.g., Kirch 1994; McCoy and Graves 2010), and many other parts of the world (e.g., Scarborough 2003; Redman 1999). Surplus agricultural production from state-controlled fields provides the funds necessary to support emerging and established elite classes.

Research on the Tarascan Empire (AD 350-1350) in western Mexico has proved useful in understanding how the control of agriculture by the state can lead to the intensification of agriculture. By closely measuring the timing of the intensification of agriculture, observed in the increased investment in agricultural infrastructure like canals and terraces, to sociopolitical development of the Tarascan Empire, Fisher and others (1999) argue that the intensification of agriculture does not occur until the development of elite classes in the region (~AD 900). Population densities, however, remained low at this time. Thus, Fisher provides a solid example of the intensification of agriculture to support increasing levels of bureaucracy in a state-level agricultural system. McCoy and

Graves (2010) provide a similar example of agricultural intensification on Hawaii, in which elites relied on surplus in order to fund their emerging elite class. Building upon archaeological research done by Kirch (1994), they explain, “the main motivator for expansion, beyond population growth, was the need for surplus to underwrite chiefly competition to increase the geographic scale of polities” (McCoy and Graves 2010).

The above examples show that agricultural intensification and political economy are tightly wedded, and frequently, the intensification of agriculture occurs in order to support elite classes and maintain bureaucracies at higher levels of sociopolitical organization. Thus, the walled fields on the Peruvian coast, which have been associated archaeologically with state control infrastructure (Kolata 1990; Téllez and Hayashida 2004), were likely more intensively used in the past than those fields that were not walled.

The Intensification of Agriculture and Soil Quality. The intensification of agriculture has been shown to have both beneficial and negative effects on soil quality in modern agricultural fields. In most modern, industrial systems and many ancient agricultural fields, the intensification of agriculture frequently leads to degradation in the quality of soils, including the loss of essential nutrients (Amiel et al. 1986; Cassman 1999; Matson et al. 1997; McAuliffe et al. 2001; McLauchlan 2007; Meyer et al. 2007; Weil et al. 1993). Some studies have shown, however, that soils can be improved with intensification, if strategies are implemented to replace nutrients removed by crop harvest (Glaser and Woods 2004; Kirch et al. 2005; Netting 1993; Sandor and Eash 1995). Unfortunately, few soil studies have been done on intensifying irrigated systems, but previous research on intensifying rainfed systems in arid environments can clarify the relationship between the intensification of agriculture and soil quality. Research on these dry farmed systems has shown variable legacies for agricultural soils from the intensification of agriculture. In this section, I provide information on soil studies from ancient agricultural systems in which intensification is likely to degrade soils, unless strategies, like fallowing or intercropping, are implemented to maintain soil quality. This discussion is the basis of the expectation that for the cases I examine, soil quality would have declined with the intensification of agriculture unless strategies to maintain soil productivity were implemented.

Stone and colleagues (1990) have documented intensification of some indigenous systems that include the use of agricultural strategies to maintain and improve soil quality. Using the Kofyar in Nigeria as an example, they argue that intensification "can be achieved using indigenous ecological knowledge, local crops, and traditional or innovative low-energy methods of turning the soil, weeding, manuring, crop rotation, soil conservation, livestock husbandry, and arboriculture" (1990:7), and thus maintain soil quality. Netting (1993), in his seminal book on intensive farming by small households, further shows how these households increased the productivity of their soils using a variety of labor-intensive techniques. These techniques include fertilizing, mulching, intercropping a diverse assemblage of crops, and the construction of irrigation canals – all of which require in depth knowledge of the local ecosystem. The tradeoff, however, is a high input of labor into fields in order to construct the infrastructure and add fertilizers to the soil necessary to maintain field productivity. These efforts, in addition to minimizing risk of food or cash shortfall due to climatic or market fluctuations, can maintain soil quality and agricultural production over the long-term (Netting 1993:45).

In West Africa, modern indigenous famers have been blamed with deforestation and the resulting degradation of soils as they intensified agriculture. Leach and Fairhead (2000) argue, however, that soil management can be seriously misunderstood if soils are not directly studied in relationship to the indigenous communities. Their research in West Africa shows that typical neo-Malthusian explanations of deforestation caused by the overpopulation of farmers and resulting overuse of soils are simply incorrect. They argue that these farmers actually enriched the soils where they lived, which created "forest islands," and encouraged the growth of trees by using their refuse as organic matter to improve soil quality (Leach and Fairhead 2000: 40). Their case study highlights that increasing population density and the intensification of agriculture can indeed result in the improvement, not the degradation, of soil quality.

The limited archaeological examples that attempt to link soil quality and the intensification of agriculture support the arguments made by Stone and colleagues (1990), Netting (1993), and Leach and Fairhead (2000) that intensification of agriculture can be accomplished while maintaining healthy soils. For example, prehistoric communities in the Amazon Basin, farming tropical soils notorious for being leached of nutrients essential for agricultural productivity, created fertile Anthrosols, or anthropogenically created soils by adding waste high in organic matter to soils (Lehmann 2003). These Anthrosols, referred to as *terra preta*, are high in organic matter and nitrogen, allowing for the intensive production of cultigens for thousands of years in the

Amazon basin (Erickson 2004). While debate continues on how exactly *terra preta* was created, it likely involved the addition of trash, high in organic matter, to areas around the villages, similar to the “forest islands” in West Africa (Lehmann 2003).

Agricultural intensification, however, has also been shown to result in a decrease in soil fertility, due to overuse and further extraction of nutrients, especially in modern, industrial agriculture (Cassman 1999; Matson et al. 1997; Meyer et al. 2007; Tilman et al. 2002). This decrease in soil fertility can force populations to intensify further in order to maintain a certain level of agricultural production, leading to further soil degradation. Arid environments, like that of the U.S. Southwest, are especially vulnerable to soil degradation, because they are normally low in organic matter that is difficult to replenish. Irrigated soils are particularly susceptible to salinization, which can be difficult to reverse (Eswaran et al. 2001; Lal 1998).

While investment in infrastructure can add vital nutrients and water to the soil, these investments can also lead to a decrease in soil quality if the soils are too intensively used or are not properly managed. For example, traditional Mexican communities in Sonora, Mexico have exacerbated floods and erosion with fencerows and channel straightening (Doolittle 2003). While these fencerows have been extolled as forms of sustainable agriculture to protect agricultural fields, Doolittle argues that these fencerows led to increased streamflows and subsequent destruction of farms and soils downstream.

Dry-farmed areas in prehistoric Hawaiian systems have also been shown to be depleted of vital nutrients, like calcium, magnesium, sodium, potassium, and phosphorus by intensive farming (Hartshorn et al. 2006; Kirch et al. 2005). In their research, Hartshorn and colleagues (2006) show that the original agricultural strategy to breakup cinders enhanced water holding capacity and nutrient release. While these fields likely maintained productivity for a period of time (although estimates have yet to be made on the time frame), prehistoric farmers did not incorporate any strategies to maintain production, simply focusing on those areas with a buried cinder horizon, which were associated with higher nutrient levels originally.

In the Tarascan Empire in western Mexico (AD 350 – 1350), Fisher (2005) documents enhancement of soil health during periods of intensive farming with the construction of terraces to increase crop production. These terraces prevented erosion on steep hillslopes, increased A horizon thickness, and led to increased crop cultivation. After this system was abandoned, however, serious degradation of soils occurred with the collapse of the terrace system and large-scale erosion of the soils previous used for agricultural fields. Fisher (2005) shows, then, that when this strategy to maintain soil characteristics – terracing – was not continued, soil quality greatly declined in this region.

These cases illustrate that soils in arid environments are highly susceptible to degradation. While some local environments initially may have relatively high soil quality, they can quickly be degraded with long-term intensive agricultural production. Soil quality can be maintained, however, if enrichment strategies, including the addition of fertilizer (or nutrients from runoff) or fallowing, are incorporated in the agricultural system. In the systems assessed in this dissertation, sedimentation of irrigated fields, the potential use of guano for fertilizer, and field structure and organization to divert nutrients and salts may be essential strategies to maintain or enhance soil quality.

Assessing Research Theme 2: How Did Agricultural Intensification of Irrigated Systems Differentially Affect Soil Quality? Soil fertility has been maintained in intensifying agricultural systems, but requires labor-intensive strategies to replace nutrients loss to crop harvest. Both case studies in the Phoenix Basin and the north coast of Peru provide comparative contexts to understand the extent to which the intensification of irrigation agriculture affects agricultural soils. In both cases, it is hypothesized that the intensification of agriculture degraded soils unless strategies were used to maintain soil quality.

To assess whether the intensification of agriculture enhanced or degraded soil quality, soils from prehistoric and more intensively farmed historic soils are compared on the middle Gila River, while soils from the more intensively farmed walled field are compared to unwalled fields on the Pampa de Chaparrí. Soil characteristics essential for understanding crop productivity, including soil texture, total nitrogen, organic carbon, sodium adsorption ratio, electrical conductivity, and available phosphorus, are analyzed to evaluate whether these intensifying systems resulted in the degradation or enhancement of agricultural soils.

Chapter Summary

This chapter has provided the theoretical background for the social and economic contexts under which the sustainability of large-scale irrigation is analyzed in this dissertation. Two research themes – the longevity and intensification of irrigation agriculture – are assessed with extensive soil analysis from prehispanic and historic fields on the middle Gila River and the north coast of Peru to understand whether these contexts resulted in the enhancement or degradation of soils in each system. Soils are analyzed for characteristics essential to crop production, including total nitrogen, available phosphorus, electrical conductivity, sodium adsorption ratio, organic carbon, and soil texture. Chapter 5 provides an extensive discussion for how these characteristics are analyzed and interpreted to assess whether long-term and intensifying irrigation resulted in the degradation or enhancement of soils in each case study region.

Chapter 3

PREHISTORIC AND HISTORIC CONTEXT OF THE MIDDLE GILA RIVER VALLEY

The land now managed by the Gila River Indian Community (GRIC) provides an excellent opportunity to study the effects of the intensification of agriculture and long-term irrigation agriculture on soil quality. With the city of Phoenix rapidly growing outward into the desert managed prehistorically by the Hohokam and historically by the O’odham (formerly referred to as Pima), the GRIC, has prevented urbanization along the middle Gila River, preserved archaeological resources, like ancient canals and agricultural sediments, and preserved the record of past human-environment interactions around farming. This research takes advantage of these preserved ancient agricultural sediments by initiating large-scale soil sampling from prehistoric (AD 750 – 1450) and historic agricultural fields (AD 1694 – 1950) to address the changing impacts of farming length and intensity on soil quality and the potential sustainability of farming practices.

This chapter presents the ecological and cultural background of the middle Gila River, located approximately 40 miles south of Phoenix, Arizona (Figure 3.1). I situate this research in the context of the environmental setting of the middle Gila River, the prehistoric Hohokam and historic O’odham cultural background, and particularly, the agricultural systems of both the Hohokam and the O’odham. In addition, I focus on documenting the intensification of agriculture during the transition from the subsistence to the market economy and the organization of management of the irrigation systems.

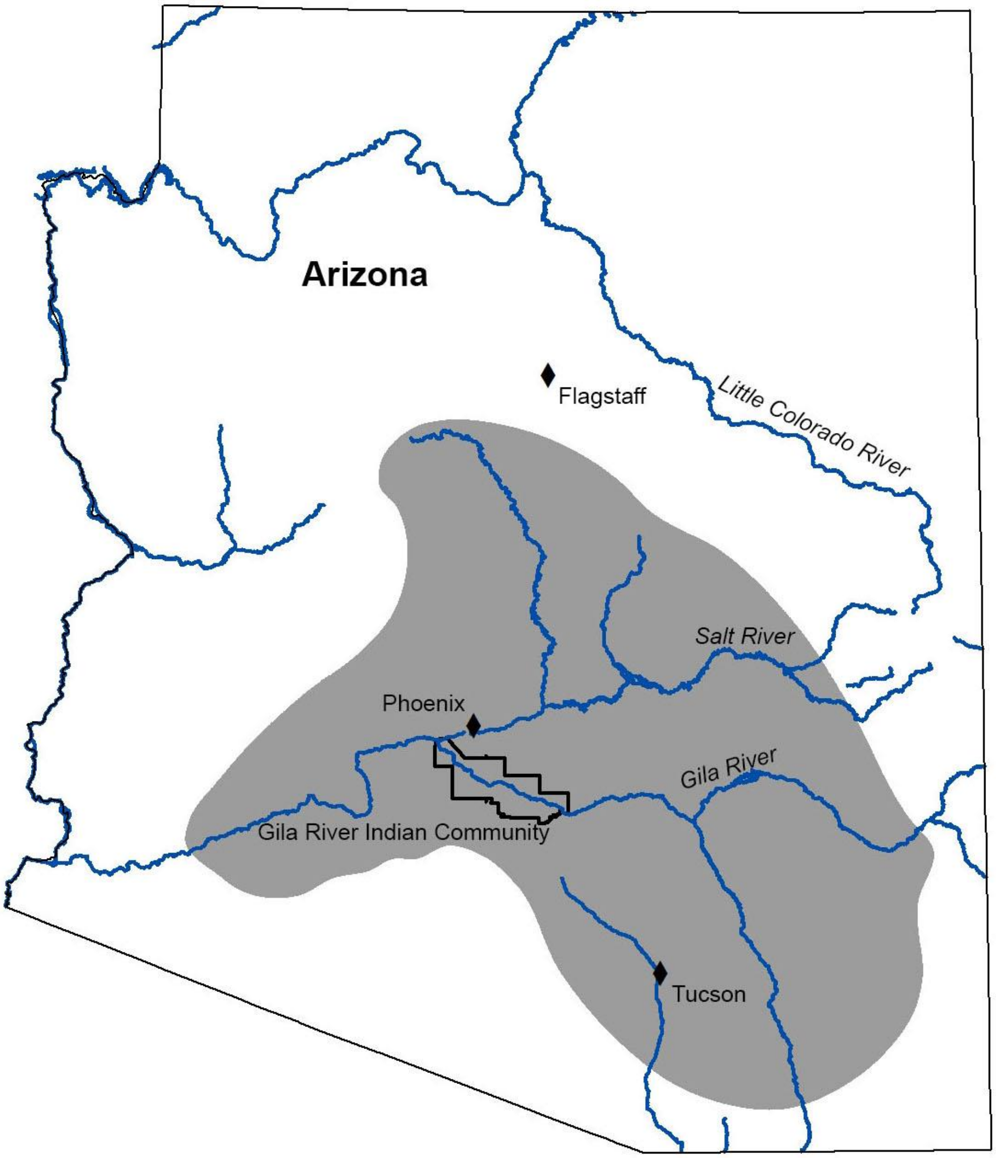


Figure 3.1: Map of the Hohokam Culture Area (in gray) and the Gila River Indian Community

Fieldwork on the middle Gila River was performed in close collaboration with the Cultural Resource Management Program at the GRIC (GRIC-CRMP), and the primary data for this case study were collected during ongoing excavations by the GRIC-

CRMP. Most of the prehistoric and historic field samples were collected in conjunction with sampling for the Pima-Maricopa Irrigation Project (P-MIP), a federally funded program currently preparing and sampling large tracts of land to expand agricultural acreage on the GRIC in the future (Woodson 2003). Some areas were also sampled as a part of archaeological investigations done in advance of new construction on the reservation, including new homes for GRIC residents. Finally, I include samples from one prehistoric field and one historic field collected in 2004 by Jonathan Sandor with assistance from employees of the GRIC-CRMP (Sandor 2010). Sandor performed fieldwork and sample collection; he and I completed laboratory analysis for the samples.

The GRIC-CRMP is well known for intensive investigations of the geomorphology of the middle Gila River (Ravesloot and Waters 2004; Waters and Ravesloot 2000, 2001) and the irrigation canals used over the past 1,000 years (Woodson 2003, 2010). This study was designed to build upon their extensive study of the geomorphology and canals of the middle Gila River by sampling the adjacent agricultural fields to garner a more complete view of the prehistoric and historic agricultural system.

Environmental and Archaeological Background of the Middle Gila River

Environmental Context of the Middle Gila River

The middle Gila River is located in arid, southern Arizona, making irrigation necessary for the large-scale production of agricultural crops. It is topographically situated in the Sonoran Desert region of the larger Basin and Range physiographic province of the western United States (Morrison 1991). The middle Gila River is defined as the 120-kilometer segment of the greater Gila River, ranging from North and South

Buttes, located 26 kilometers west of the Florence region, to the confluence of the Gila and Salt Rivers. The valley is broad compared to other rivers in Arizona, ranging from 5 kilometers to 20 kilometers in width. It also has a low gradient downstream from west to east through the middle Gila Valley, only decreasing in elevation by 176 meters, averaging 1.4 meters per kilometer. These characteristics of the middle Gila River make it ideal for the construction of a large-scale irrigation system for agricultural production (Woodson 2003).

The area typically receives approximately 200 mm of rainfall per year with an average annual temperature of 20.6º C (Johnson et al. 2002; Sheppard and Comrie 2002). The combination of the high temperatures (average of 38º C in the summer) and low rainfall result in moisture-deficit in the region, with evapotranspiration exceeding precipitation in most years, making long-term, successful agricultural production without irrigation nearly impossible (Waters 1996). Most of the annual rainfall comes in heavy thunderstorms during the summer monsoon season in July and August, when wind patterns and moisture shifts north from Mexico into the region (Shafer 1989). A second season of rainfall occurs during the winter monsoon, when gentler rains enter the region from storms coming in from the Pacific Ocean between December and February. Rainfed crops, like agave and other succulents were cultivated in the uplands and bajadas around the river, which diversified Hohokam and O'odham diet (Bohrer 1970, 1991). Despite low and unpredictable rainfall in the region, the Gila River draws water off a broad area of uplands in Arizona and New Mexico, so water for irrigation is reliable even during times of low precipitation (Waters and Ravesloot 2000).

The Sonoran Desert is renowned for its plant and animal diversity (Nabhan et al. 1982; Nabhan 1986; Rea 1997). The general vegetation pattern is defined as Sonoran Desert scrub (Brown 1994). With a wide range of plants available in the lower river valleys, as well as wild resources and other anthropogenically-encouraged plants and cultivars, like cholla and agave, available in adjacent uplands, prehistoric and historic communities had access to a diverse resource base (Bohrer 1970, 1991; Fish and Fish 1992). Unfortunately, the study area underwent serious erosion and desertification due to the loss of water on the middle Gila River in the late AD 1800s, so vegetation communities today do not represent what would have been present during in the prehistoric and historic periods (DeJong 2011).

Previous Research on Soils on the Middle Gila River. Soils on the middle Gila River are highly varied and their geomorphic surfaces were largely formed by alternate periods of alluvial aggradation and downcutting over thousands of years (Ravesloot and Waters 2004; Waters and Ravesloot 2000, 2001). Although studies on the agricultural soils on the GRIC are recent additions to our understanding of the GRIC landscape, the study area has been subject to intensive documentation of the geomorphological development and of the canal systems (Huckleberry 1994, 1995; Ravesloot and Waters 2004; Waters and Ravesloot 2000; Woodson 2003, 2010).

Extensive geomorphological research on the middle Gila has provided excellent information on how the middle Gila River Valley has formed geologically, has defined periods of alluvial deposition and downcutting, and has clarified the development of prehistoric and historic irrigation systems in relation to the streamflow of the river

(Figure 3.2). Geomorphology influences soil formation and characteristics, so these previous geomorphological studies on the middle Gila River allow for the sampled sites to be accurately assigned to the correct geomorphological context, which was also field checked during sampling (Ravesloot and Waters 2004; Waters and Ravesloot 2000; Waters 2008). By only comparing soils within the same geomorphic context, the anthropogenic impacts of the intensive production for a market economy and long-term irrigation on soils can be isolated.

Prehistoric and historic agricultural fields for this study were sampled on two different river terraces along the Gila River, including the young Holocene (T-2 on GRIC Maps) and the older Pleistocene Terraces (T-3 on GRIC Maps). Most historic fields are found on the younger Holocene Terrace, as these terraces would have been present during more recent time periods, while prehistoric fields are frequently found on the older, Pleistocene terraces. Historic sources also document that many of the earliest irrigated fields are located on the south side of the river and near the center of the reservation in the Casa Blanca region of the GRIC (DeJong 2011; Woodson 2003), thus sampling was concentrated in that area to sample earlier historic agricultural fields (Figure 3.8). Prehistoric and historic fields, however, were sampled on both terraces to ensure comparability of soils between both time periods.

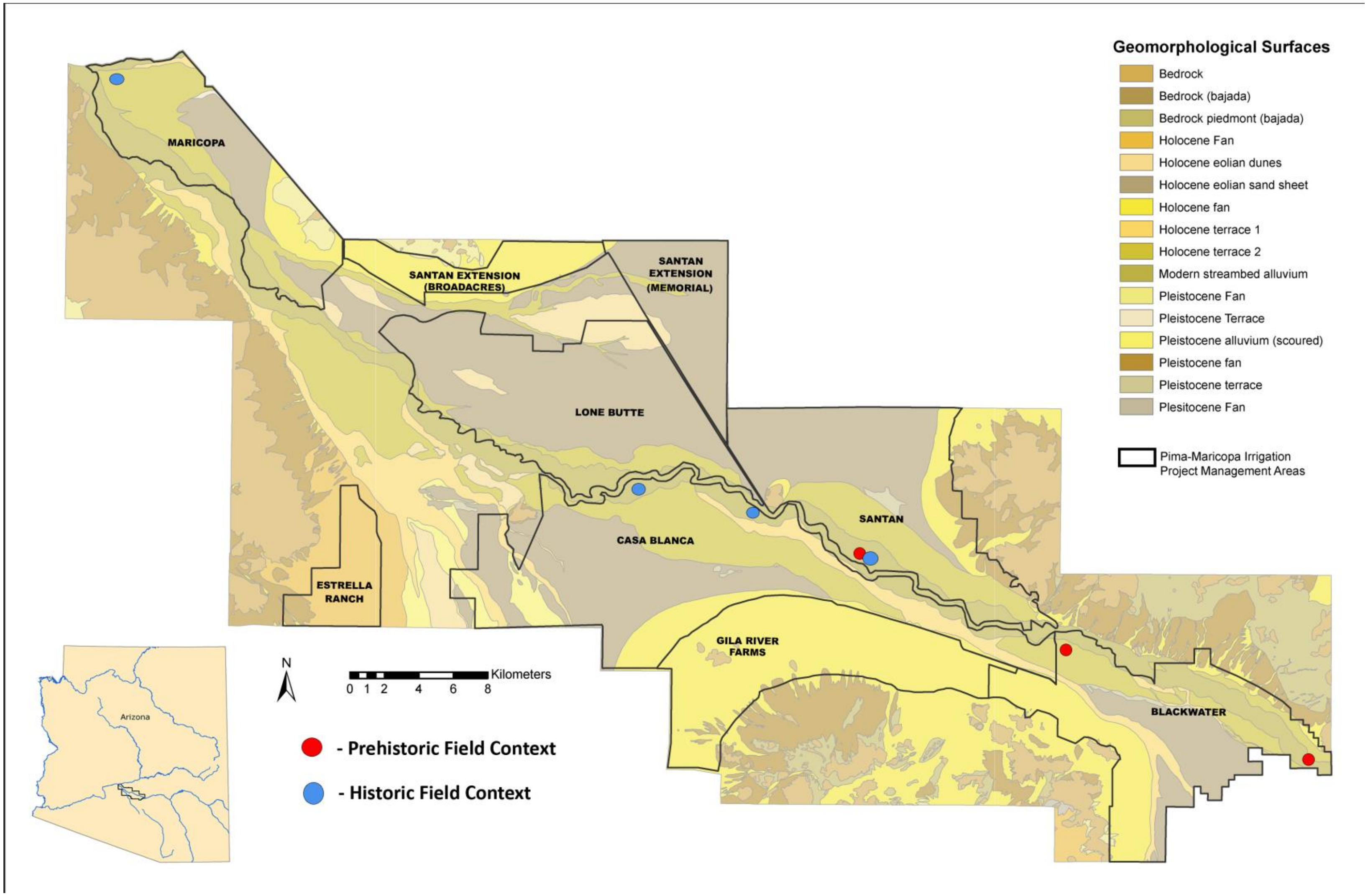


Figure 3.2: Geomorphology of the Middle Gila River with Pilot Sampling Sites Plotted

Much of the research on soils on the middle Gila River has also focused on canal development and canal sedimentation by analyzing deposits within the canals themselves (Huckleberry 1992, 1995; Palacios-Fest 1994; Purdue et al. 2010; Woodson 2003, 2010). These studies have documented different flow regimes of the canals, the ecodynamics of the middle Gila River, the command area of agricultural fields, and sedimentation processes of agricultural fields. Huckleberry (1995), for example, argues that times of major downcutting or flooding of the middle Gila River would have resulted in disastrous consequences for the stability of the Hohokam irrigation system. Major channel changes of the middle Gila River would have resulted in the complete abandonment of entire canal systems and/or the unexpected investment of large amounts of labor into the dredging of existing canals and headgates (Ravesloot and Waters 2004). While these studies of canal deposits clarify how the irrigation canals contributed to Hohokam and O’odham cultural and economic development, the adjacent agricultural fields have been surprisingly ignored, perhaps due to the inability to identify these buried agricultural sediments until the development of the methodology designed for this dissertation.

This lack of evidence regarding the quality of agricultural soils along the middle Gila River has not prevented many archaeologists from using other sources of data to speculate about the possibility of salinization in prehistoric and historic agricultural fields. These speculations have led to widely divergent opinions on whether the Hohokam and O’odham irrigation agricultural systems were susceptible to salinization and a decrease in soil quality (Ackerly 1988; Dart 1986; Haury 1976; Huckleberry 1992, 1999; Krech 1999; Palacios-Fest 1994). Some researchers argue that the longevity of the

Hohokam irrigation system and ethnographic observations of O'odham flushing salts from the soils indicate that salinization was effectively managed (Ackerly 1988; Sandor 2010), while others believe that due to the prevalence of historic salinization along the Salt River, the Hohokam would have likely faced the same problems (Krech 1999). Despite the pages of literature devoted to hypotheses regarding the salinization of Hohokam agricultural fields, this hypothesis is largely untested with soil samples from prehistoric and historic agricultural fields.

Only a few pilot studies on the agricultural soils have been done on the GRIC study area. Limited sampling in 2004 by Sandor (2010) on prehistoric and historic agricultural fields at the GRIC has identified areas where more research is needed. Based on samples from one prehistoric and one historic irrigated field (that were also ultimately included in this dissertation), he argues that the salinity of the irrigated soils is high enough to reduce maize, bean, and squash production (Sandor 2010: 42). It is unclear, however, whether this high level of salinity is due to the natural properties of the landscape, which is inherently high in salt content, or anthropogenic processes, like long-term irrigation. Sandor (2010) stresses the need for more research and sampling to understand anthropogenic changes to the soil associated with long-term irrigation.

More recent research on the irrigated fields on the GRIC has aggregated data collected over decades by the GRIC-CRMP and a Cultural Resource Management firm (the now-defunct AgServices Company) that show evidence for anthropogenic development of the soils along one canal system on the middle Gila River (Woodson et al. in review) – something that will be discussed in depth in Chapter 6. Because of the aridity of the Phoenix Basin and the naturally high salt and sodium content of the soil, these soils originally may have been poor for agricultural production. This recent research, however, has shown that the input of water, nutrients, and sediment from irrigation canals may have been necessary for long-term agricultural success in the region – something reaffirmed by the data presented in this dissertation. Sandor (2010) also describes a thick mantle of silt loam (77 cm) overlying older, well-developed argillic horizons, reflecting sedimentary deposition of fine sediments by canal irrigation.

Prehistoric and Historic Cultural History of the Middle Gila River. Situated in the Phoenix Basin in central Arizona, the middle Gila River is located at the heart of the prehistoric Hohokam and historic O'odham populations (Table 3.1). People have lived along the middle Gila River for thousands of years, with archaeological sites dating to the middle Archaic period (5000 – 1500 BC), although older sites dating to the Paleo-Indian (10,000 – 8,500 BC) and Early Archaic (8,500 – 5,000 BC) periods are found throughout the Phoenix Basin (Huckell 1984). Small agricultural villages emerged in the Phoenix Basin around 1500 BC, although villages this early have not been located on the GRIC, probably due to more recent alluvial deposition burying early archaeological sites (Huckell 1996; Loendorf 2010). With the growth of these agricultural villages in the Phoenix Basin, small canals were constructed, as evidenced at places like Las Capas, along the Santa Cruz River, where archaeologists found extensive canal systems dating to 1250 – 500 BC (Mabry and Davis 2008).

Table 3.1: Hohokam and O’odham Chronology

Period	**Phase**	**Date Range (AD)**
Pioneer	Red Mountain	100-450
	Vahki	450-650
	Estrella/Sweetwater	650-700
	Snaketown	700-750
Colonial	Gila Butte	750-850
	Santa Cruz	850-950
Sedentary	Sacaton	950-1150
Classic	Soho	1150-1300
	Civano	1300-1450
Protohistoric		1450-1694
Early Historic	Spanish/Mexican Era	1694-1846
Late Historic	American Era	1846-1950

The Hohokam population subsequently exploded with the construction of major irrigation systems during the late Pioneer Period (AD 1 - 750), used to cultivate maize, beans, squash, and cotton (Dean 1991; Doyel 1991; Haury 1976; Howard 1993; Mabry 2002; Woodson 2003, 2010) along the Salt and Gila Rivers. The first plainware and redware ceramics were also made at this time (Doyel 1993; Wallace et al. 1995). The middle Gila River operated as a demographic center for the prehistoric Hohokam, with major settlements like Snaketown dominating the cultural landscape (Haury 1976). The first ballcourts appeared during the Colonial Period (AD 750-900), and the subsequent Sedentary Period (AD 900-1150) was a time of great expansion demographically, agriculturally, and economically for the Hohokam with the construction of an extensive network of ballcourts, extending from south of Tucson to north of Flagstaff. Some have argued that ballcourts served as meeting places, perhaps even as markets, for extensive bartering of ceramics and perhaps other materials that may not be archaeologically visible, like textiles (Abbott et al. 2007; Abbott 2009; Hunt 2011). It was during this time that the canal systems on the middle Gila River reached their greatest extent (Woodson 2010), indicating that irrigation agriculture was producing a reliable surplus to support some specialization of ceramic and cotton production for exchange.

The Classic Period (AD 1150 – 1450) ushered in many changes including the abandonment of the ballcourt network, construction of platform mounds, contraction of the Hohokam interaction sphere, weakening of the Hohokam exchange network, change in burial practices, and the introduction of different ceramic types to the region (Abbott et al. 2007; Abbott 2009; Bayman 2001; Crown et al. 1991; Doyel 1991a). These changes during the Classic Period were accompanied by a slow demographic decline in the Phoenix Basin later in the Classic Period from the AD 1300s until abandonment of the region in the mid AD 1400s (Abbott 2003; Ingram 2010).

When the Hohokam population largely disappeared in the Phoenix Basin around AD 1450, most of the prehistoric canal system fell out of use (Abbott 2003; Wells et al. 2004; Wilcox and Masse 1981). Many archaeologists have attempted to address what may have caused the depopulation of one of the most densely populated regions of North

America at this time. Archaeological research has shown that health was declining at some places during the Classic Period (Sheridan 2003), although some claim that poor health was not widespread and originally may have been overstated (McClelland and Lincoln-Babb 2011). Others have cited streamflow anomalies throughout the late AD 1300s and early 1400s, which led to successive droughts and floods to which the Hohokam could not properly respond to get enough water to their fields (Graybill and Nials 1989; Graybill et al. 2006). Others hypothesize that salinization of agricultural fields decreased the ability of the Hohokam to maintain food production (Dart 1986; Haury 1976; Palacios-Fest 1994). Many of these factors may have been developing throughout the AD 1300s and 1400s, leading to a multi-factored explanation for the depopulation of the Phoenix Basin. Regardless of the many hypotheses concerning the causes for collapse of the Hohokam system by the 15th century the canals and adjacent fields and settlements were no longer functioning as they had, and most, if not all, of the population had moved away.

This collapse of the Hohokam population and institutions ushered in the Protohistoric period on the middle Gila River (AD 1450 – 1694). The Protohistoric period has been little studied by archaeologists due to the scarcity of archaeological materials, resulting from small and scattered populations at this time. Earliest historic observers in the region doubted the relationship between the large archaeological remains left by the Hohokam and the small, indigenous populations residing on the landscape during the early historic period (Fewkes 1912; Russell 1908). Because of the differences in the archaeological record between Classic Period Hohokam and Protohistoric

O’odham, many researchers have speculated that the Hohokam and the O’odham were distinct cultural groups (Russell 1908). However, most O’odham have long-claimed continuity with the Hohokam, despite the uncertainty in the archaeological record (Loendorf 2010). Recent archaeological and historic research has taken a more nuanced view of the processes affecting historic populations and has shown that cultural continuity can be observed in artifacts, most specifically lithics and ceramics, between the prehistoric Hohokam and the historic O’odham, despite scant archaeological evidence (Doelle 2002; Loendorf 2010; Wells et al. 2004).

The small, dispersed protohistoric population occupying the middle Gila River Valley was first recorded by Father Eusebio Kino, who arrived in the region in AD 1694 (Bolton 1919). We are largely reliant on historic Spanish documents, such as those by Kino, for information about the O’odham interactions with the Spanish at this time, as little archaeological investigation has been done. While Kino recorded little about the agricultural system, he documented five to seven ranchería style villages spread out along the middle Gila River with no supra-village organization (Winter 1973). With the entrance of Kino also came many Spanish-introduced crops and goods, like the horse, wheat, and metal tools, which the O’odham acquired shortly after Kino’s arrival, although it remains unknown when exactly the O’odham along the middle Gila River were first introduced to these technologies.

Shortly after the arrival of Kino, Apache raiding of O’odham villages increased, with the introduction of the horse allowing the Apache to more efficiently steal from the O’odham (Upham 1983). Kino noted many instances of raiding throughout the Pimería

Alta (the middle Gila River represented the extreme northern section of this region, which extends through southern Arizona into northern Mexico), but Apache raiding did not become an issue on the middle Gila until after his arrival and the introduction of the horse. With this increase in Apache raiding, the O'odham were forced to move their rancherías toward the center of the valley, aggregating in defense against the mobile Apache (Hackenberg 1962; Upham 1983).

During the AD 1700s and early 1800s, the majority of Spanish population and influence was restricted to extreme southern Arizona, mostly focused in areas south of Tucson. Missions, such as San Xavier del Bac and Tumacácori, exerted control over indigenous populations in the region. Due to fear of Apache raiding along the middle Gila River Valley, however, the Spanish never fully missionized the O'odham living in this area, leading to interesting differences in the economic development between the O'odham along the middle Gila River and other indigenous groups in extreme southern Arizona (Figure 3.3). The Gila O'odham, then, represented a frontier for the Spanish moving into the Pimería Alta. Despite being a frontier region, historic documents indicate that the O'odham were actively trading with the Spanish to the south (Ezell 1961).

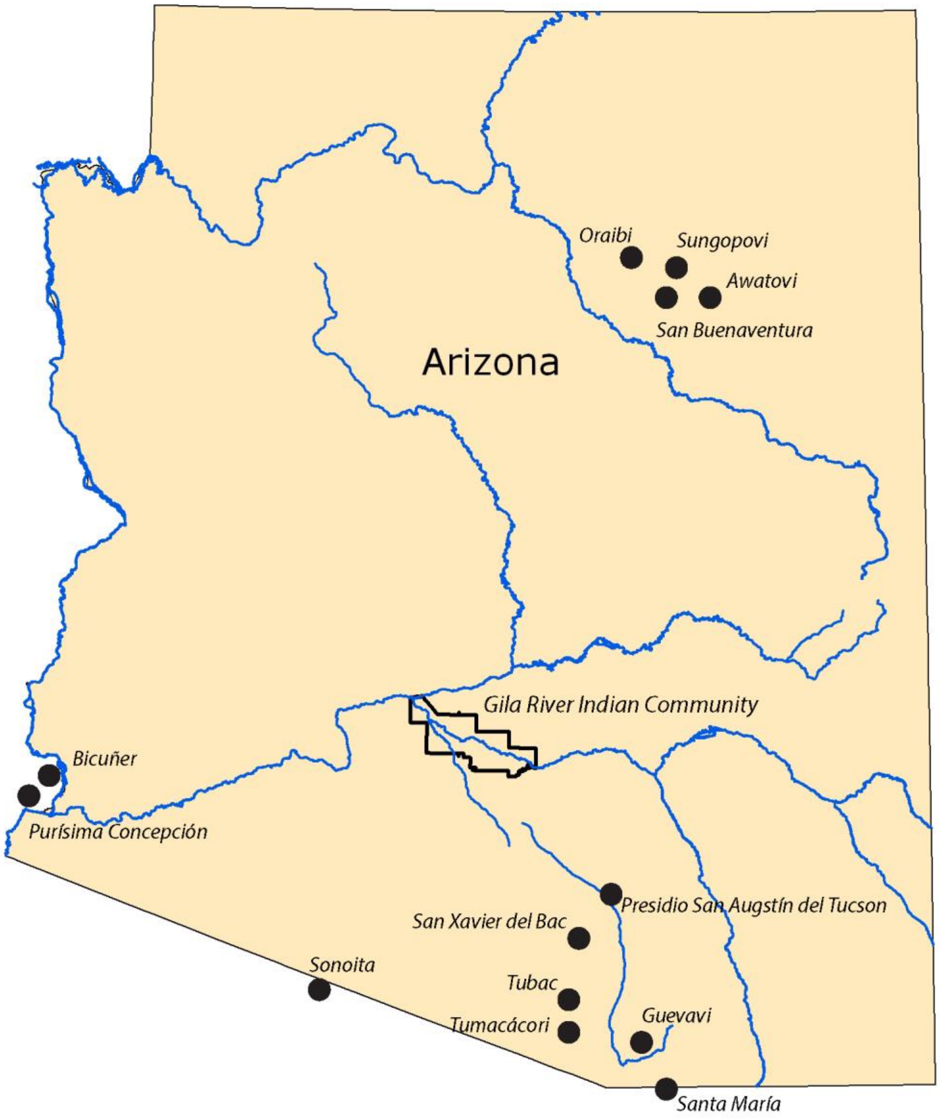


Figure 3.3: Map of Major Spanish Settlements and the Location of the Gila River Indian Community in Arizona

In 1821, Mexico gained independence from Spain, ending the Spanish period along the middle Gila River, but little changed for the O'odham on the middle Gila River and their interactions with the Spanish and Mexican colonizers (DeJong 2009; Wilson

1999). The mid AD 1800s, however, brought many changes at different scales to the middle Gila River. With their win in the Mexican American War, the United States federal government took control of the middle Gila River in 1846 and increased the military presence in the region. The increased military presence led to a reduction in Apache raiding in the mid to late AD 1800s, allowing for more people to enter the region. In 1848, gold was discovered in California, and the Southern Trail was established through the middle Gila leading to an estimated 60,000 people moving through there. These new American explorers relied heavily on the O'odham along the middle Gila, and the O'odham responded by further expanding their irrigated acreage and increasing emphasis on wheat production. In 1851, the Gadsden Purchase officially made the territory south of the Gila River to today's border with Mexico part of the United States. In 1859, the federal government established the first reservation in Arizona – the Gila River Indian Community – officially recognizing the Gila O'odham as a native group in the region (Wilson 1999).

The mid AD 1800s was a time of great economic success for the O'odham, as they actively participated in the market economy, trading their agricultural crops for wares, including metals, with the Americans entering the region. The economic success exploded over the following decades, as documents show the O'odham were selling record quantities of crops to the United States travelers and military (DeJong 2009). This economic success changed, however, with the loss of water along the middle Gila River due to American farmers moving upstream and diverting water for irrigation in areas like Coolidge and Florence in the AD 1870s. With the loss of water, the O'odham faced mass poverty and starvation. Because agricultural production was greatly reduced at this time, the O’odham resorted to a number of strategies to avoid these fates, including relying on federal food donations (DeJong 2009), moving upstream of designated reservation areas to try to capture irrigation water before the river dried up (DeJong 2011), harvesting mesquite along the river to sell as firewood to the city of Phoenix (Bigler 2007; DeJong 2011), and migrating to Phoenix to fulfill service jobs (DeJong 2011), resulting in poverty that remains among members on the GRIC today.

Agriculture, Economic Development, and Land Use Intensification on the Middle Gila River

Of particular interest to this dissertation is the documentation of irrigation management, traditional farming, and agricultural intensification observed archaeologically, historically, and ethnographically on the middle Gila River. The dynamism of the environmental and cultural forces in the middle Gila River Valley over the past 1,000 years led to marked changes in how the Hohokam and O’odham managed their agricultural system, reacting to both natural and cultural changes (Ravesloot et al. 2009; Redman et al. 2009). Despite variable streamflow, low annual precipitation, and incoming groups, the Hohokam and the O’odham maintained a highly productive agricultural system that created surplus for barter and the market, respectively, that provides a fascinating case study to document the ecological effects of long-term irrigation.

Irrigation Management and Social Organization of the Long-Lived Prehistoric Canal Systems in the Phoenix Basin (AD 700 – 1450)

The management of the Hohokam irrigation system has been the subject of much debate by archaeologists, resulting in a number of hypotheses regarding the level of centralization of decision-making. Management likely changed over the course of prehistoric farming, especially with the transition from the Sedentary (A.D. 950 - 1100) to the Classic periods (A.D. 1100 - 1450). The following section provides archaeological evidence that the irrigation systems were likely managed at the canal system while households controlled agricultural fields. This management system is much less centralized and complex than that seen in coastal Peru, as discussed in the following chapter.

People have occupied the middle Gila River Valley for thousands of years, resulting in a diverse suite of land uses. The prehistoric Hohokam constructed the largest canal system in the prehispanic New World north of Peru, with extensive canal systems on the Salt and Gila Rivers in the Phoenix Basin (Scarborough 2003; Woodson 2003; Woodson 2010). Prehistoric Hohokam groups began large-scale, multi-village irrigation on the middle Gila River during the Snaketown phase (AD 650 – 750), although some smaller irrigation systems were built in the centuries before (Doyel 1991b; Haury 1976; Howard 1993; Mabry 2002; Woodson 2003, 2010). Nineteen prehistoric canal systems were constructed on the middle Gila River, three of which were fed by the Salt River but entered the middle Gila watershed near the confluence of these two rivers (Figure 3.4; Woodson 2003, 2010). These canal systems fed tens of thousands of acres on the GRIC, some miles from the Gila River, and provided the water necessary to grow crops on this arid floodplain. Because of their importance to Hohokam social organization and agricultural production, these irrigation canals have received considerable attention from archaeologists (Abbott 2000, 2003; Doyel 1981; Fish and Fish 1992; Fish 1996; Gregory 1991; Howard 1993, 2006; Hunt et al. 2005; Teague 1984; Woodson 2003, 2010).

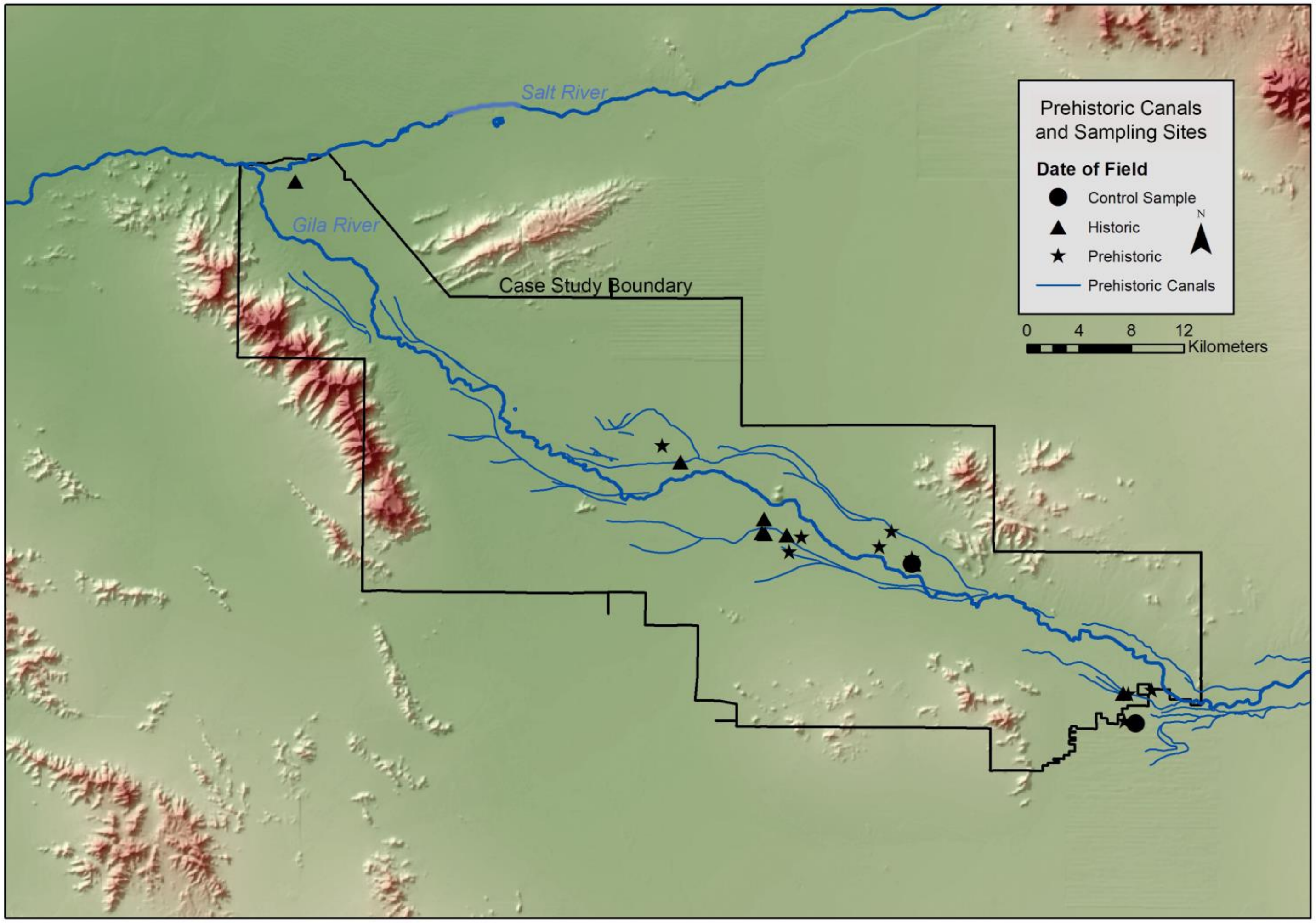


Figure 3.4: Map of Middle Gila River Prehistoric Canals

In these irrigated fields, prehistoric and historic communities cultivated maize, beans, squash, and cotton and encouraged a diverse set of wild plants, like agave and cholla, in rainfed upland areas (Bohrer 1970, 1991; Fish 2000; Gasser and Kwiatkowski 1991; Gasser 1979; Rea 1997). Hohokam irrigation agriculture was intensive, mostly subsistence based (Henderson and Clark 2004), and able to produce enough food for the local population of ten thousand or more people in the Phoenix Basin during the Sedentary and Classic periods (Hill et al. 2004; Sheridan 2003; Wilcox 1991; Woodson 2010). Hohokam irrigation canals allowed for at least one, if not multiple, crops to be produced annually, and, for almost a millennium, required extensive cooperation along each main canal (Hunt et al. 2005).

The Structure of Agricultural Production. Prehistorically, little is known about the structure and quality of agricultural fields, despite intensive study of the canal systems. While the majority of research on irrigation farming has focused on the construction and social organization of the extensive canal system built by the Hohokam (see above), some studies have been done regarding the creation and structure of the agricultural fields themselves. A limited number of studies have focused on the prehistoric agricultural fields along the Salt River and intermittent washes to the north. Howard (2006) undertook an extensive study of the social organization of household fields along the Salt River and found that agricultural fields was likely managed at the household level, similar to ethnographic evidence of how the O’odham managed their agricultural fields historically along the middle Gila, but irrigation management likely relied on higher levels of organization, managed along each main canal along the Salt River. Howard (2006) based these conclusions on extensive investigations of canals and demographic change along the Salt River under which water resources would have become increasingly scarce, necessitating the need for negotiation over the distribution of water resources.

Henderson and Clark (2004) draw upon ethnographic and archaeological data to define the structure of agricultural fields using the presence of field houses over the course of 1,000 years along the Salt River; their conclusions are similar to Howard’s (2006). With extensive mapping of field houses on the Salt River floodplain, fieldhouses were continuously being reconstructed throughout Hohokam prehistory. Their data indicate that these houses were built in the same places over time, even during the middle Sedentary Period with the development of marketplaces at the ballcourts, which they argue indicate that the households held control over their fieldhouses and, thus their land and agricultural fields. Their data also show that Hohokam agricultural practices likely reflected those of the smallholder agriculturalists defined by Netting (1993) and briefly discussed in the previous chapter, since they operated at a similar scale and produced food for their own consumption and some surplus for barter and exchange.

Woodson (2010) reiterates the conclusions by Howard (2006) and Henderson and Clark (2004) with data from canal systems on the middle Gila River. With extensive data from four canal systems, Woodson infers the “command area,” or the field area, managed by these canal systems, based on the location and length of field laterals, which deliver water to the fields. He found that these irrigation systems were managed at the level of the individual canal systems, similar to the Salt River, based on how much area the canals would have watered and the amount of water available along the river. The availability of water, or lack thereof, would have necessitated management of water higher than the individual or household level.

While the historic O’odham were clearly embedded in the market economy, the level at which the prehistoric Hohokam participated in a market economy is debatable, and most Hohokam farmers likely cultivated crops mainly for their own subsistence. The Hohokam’s largely subsistence economy, then, provides an excellent baseline to compare to the O’odham’s entrance in the market economy in the subsequent centuries. Evidence for the specialized production of pottery throughout the Salt and Gila River Valleys is strong, and these wares were distributed across both the Salt and Gila River Valleys (Abbott et al. 1999; Abbott 2000, 2003). Abbott and others (2007, 2009) have argued that marketplaces formed in conjunction with the expansion of the ballcourt network during the middle Sedentary Period from AD 1000 - 1070. Evidence of these periodic marketplaces comes from specialized and highly concentrated production of ceramics on the lower Salt River, which were then distributed across the ballcourt network throughout Arizona. With the collapse of the ballcourt network in AD 1070, the foundation for the market was lost, and specialized production of ceramics decreased (Abbott 2007: 476).

Many archaeologists have speculated that cotton may have acted as a “cash crop” prehistorically (Doelle 1980; Doyel 1991a; Gasser and Kwiatkowski 1991; Teague 1998). Since cotton can only be grown in a few places in the U.S. Southwest (limited to irrigated regions in southern Arizona before AD 1100, and then distribution expands to the Rio Grande, including northern pueblos and the Mimbres region, and then the Hopi region shortly after that date), cotton would have been in high demand for the creation of textiles throughout the Southwest (Hunt 2011; Minnis 1985; Teague 1998). Hunt (2011) argues that this demand would have driven the expansion of the irrigated agricultural system in the Hohokam region. Because the trade of textiles has little archaeological visibility, however, this hypothesis is difficult to test (Hunt 2011). Regardless, macrobotanical evidence indicates that cotton was traded from the Hohokam region to northern sections of the U.S. Southwest, indicating that Hohokam agriculturalists were producing a large surplus of agricultural crops for barter and exchange (Doelle 1980; Doyel 1991a; Gasser and Kwiatkowski 1991; Teague 1998).

Clearly, the prehistoric Hohokam specialized in the production of pottery and perhaps cotton, necessitating the production of a surplus of agricultural crops to support non-farming specialists. While evidence exists for a brief period of market exchange of ceramics at occasional meetings at ballcourts from AD 1000 – 1070 (Abbott et al. 2007; Abbott 2009), these marketplaces were used only for a few decades, were periodic in their use throughout the year, and were not controlled by an overarching authority (Abbott 2000; Abbott et al. 2007). It appears that while Hohokam farmers were specializing in the production of pottery, they were still largely growing crops for their own consumption from the structure and size of agricultural fields (Henderson and Clark 2004).

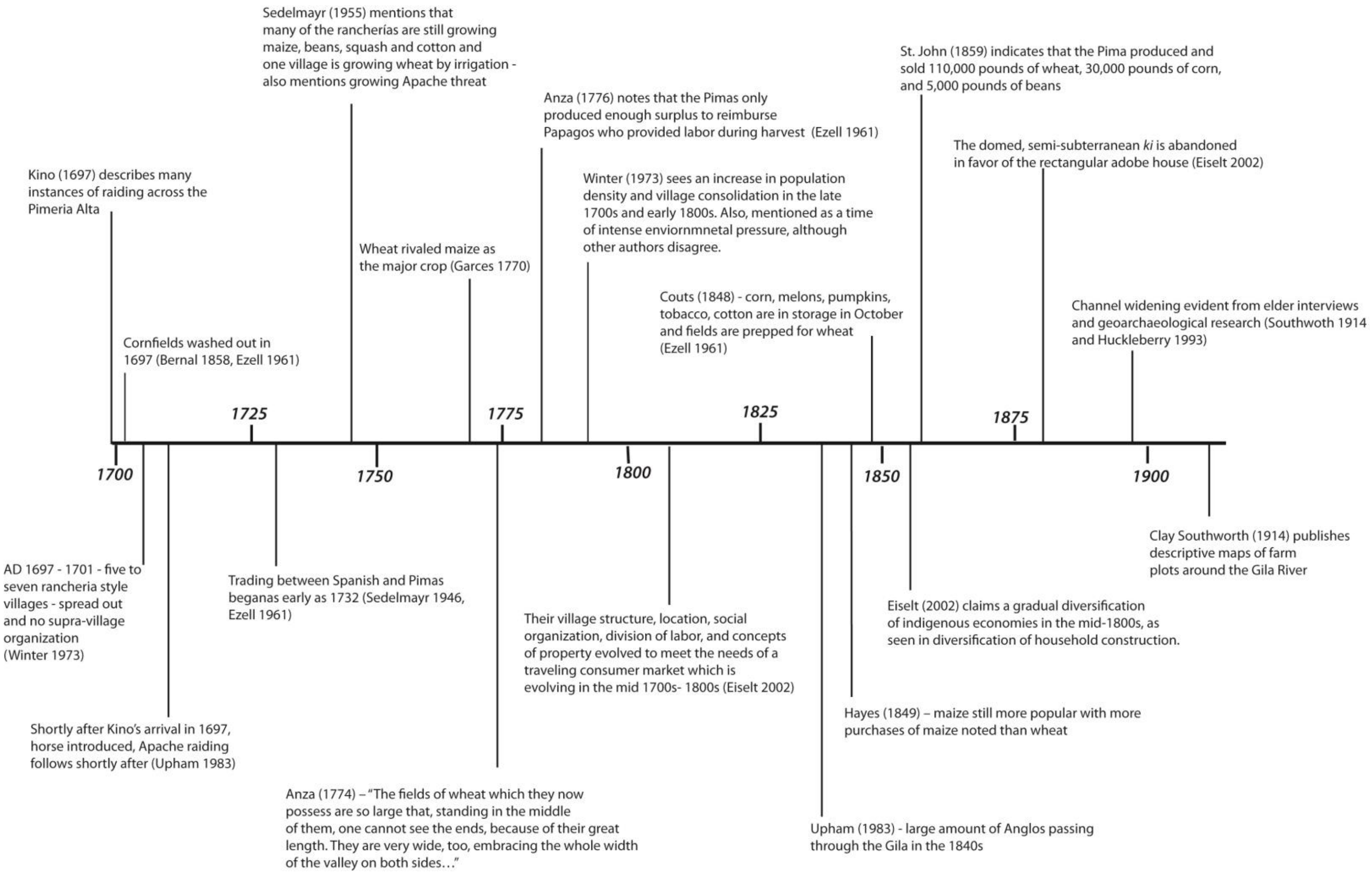
The Intensification of Agriculture during the Early Historic Periods (AD 1694 – 1870)

In the previous section, I argued that the Hohokam practiced a largely subsistence based agricultural system, with people producing crops for their own consumption and a surplus for barter to other regions of the U.S. Southwest and to support specialists. While the historic O’odham irrigation system never reached the extent or complexity of the prehistoric Hohokam system, using a combination of archaeological, historical, and ethnographic data sources, I contend that the O’odham intensified agriculture over that practiced by the prehistoric inhabitants of the region, as they adopted cash crops with the introduction of a market economy until the loss of water on the middle Gila in the AD 1870s.

In order to measure the intensification of agriculture during the historic period, I analyze historic sources from Spanish missionaries (Early Historic) and the United States explorers and military (Late Historic) to document increases in population density (with the combination of settlement extent and demographic estimates) and maize and wheat yield. These data show that with increasing population density and access to a market, the O’odham intensified agriculture to produce crops to sell to Spanish and American incomers. Other authors (DeJong 2009; Doelle 1981; Doelle 2002; Upham 1983; Wilson 1999) have assembled many of these data, but their calculations are checked, when possible, and restructured for the purposes of this dissertation. These documents provide data on where settlements were located, population size, irrigated acreage, and the amount of crops produced in certain years, and can provide insight into the level of aggregation and crop production over time, both of which are important indicators of agricultural intensification.

Over a period of approximately two centuries, the O’odham adapted to Spanish introduction of new crops and missions, Apache on horseback raiding their villages, and Americans needing access to food (Figure 3.5). Despite the colonization of southern

Arizona by the Spanish, the first part of the historic period (AD 1694 – 1870) was a period of great economic success for the O'odham living along the middle Gila River, as the O'odham sold a surplus of crops to the influx of newcomers. In the following section, I argue that during the historic period (1) settlement pattern and demographic estimates indicate increasing population density, (2) increasing population densities led to the creation of a tribal government, allowing for a cooperative structure for an irrigation system, and (3) intensive irrigation agriculture and wheat were adopted to meet the demands of a market economy. These factors indicate that O'odham agriculture shifted from subsistence-based agriculture, largely practiced by their ancestors prehistorically, to a cash-based agricultural system in response to market forces.



* No Spanish writer ever reports a famine on the Gila River

Figure 3.5: Timeline of Agricultural Changes During the Historic Period

The Increase in Population Density. One of the main drivers of the intensification of agriculture and land use is increasing population density (Boserup 1965; Netting 1993). Here, I use data on the settlement extent of historic rancherías and demographic estimates to argue that population density in the study area increased during the historic period. Consequently, O'odham agriculturalists most likely intensified agricultural production to maintain previously high yields of agricultural crops on a smaller extent of land. The increase in population density also had important implications for the ability to create a tribal government and to construct and manage a large-scale irrigation system, both of which are addressed in the following sections.

Figure 3.6 shows the extent of O'odham settlement along the middle Gila River from AD 1702-1877. Upham (1983) previously compiled these data (from Ezell 1961; Hackenberg 1962) to show the level of aggregation across the middle Gila River during the historic period, and his numbers have been confirmed against the original sources. The extent of settlement (in miles) shows how much of the landscape along the middle Gila River was occupied during a given year, and thus provides insight into the level of aggregation. For example, a larger extent of settlement indicates that the settlements were more dispersed across the landscape.

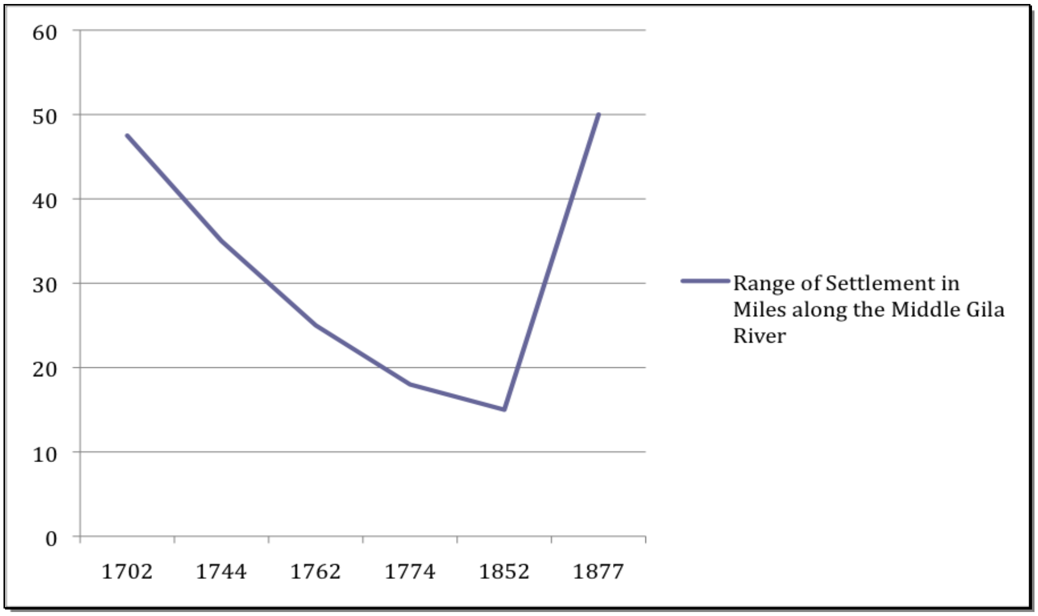


Figure 3.6: Settlement Extent in the Middle Gila River Valley (in miles)

As Figure 3.6 shows, the extent of settlement decreased throughout the historic period, until the late AD 1800s, when extent expanded again in response to the loss of water upstream and the O'odham moved to other parts of the middle Gila to try to maintain agricultural production. Although settlement extent shrank throughout the historic period until the mid AD 1870s, population data are needed to confirm that population numbers remained the same on a smaller extent of land, indicating an increase in local population density. For example, settlement extent could have been shrinking due to a loss of population from Spanish-introduced diseases.

Figure 3.7: Population Numbers of the Middle Gila River Valley from Historic Documents

Figure 3.7 shows the best estimates of population at during the historic period and tells a complicated story of demographic highs and lows (Doelle 1981). Population appears to have undergone a series of shifts over the historic period, although it is unclear whether these shifts are real or a product of rough estimates made by incoming explorers. Overall, however, the data indicate that population increased during the historic period, especially from the initial population observed when the Spanish first arrived in the late AD 1600s. With population hovering around 4,000 after initial Spanish observations, the O'odham still fell victim to diseases introduced by the Spanish (see Garcés 1965), but the population lost from disease was replaced by in-migration from other groups, who sought refuge from the Apache (Bolton 1919; Bolton et al. 1930; Doelle 1981, 2002).

Regardless of these shifts, population generally increased throughout the historic period, until the loss of water in the late AD 1800s. At the same time, settlement contracted in the early AD 1700s, as people aggregated toward the center of the middle Gila River Valley (Doelle 1981; Upham 1983; Wilson 1999). This increasing aggregation has been attributed to a few driving processes. Upham (1983) argues that this aggregation is intrinsically linked to Apache raiding, and statements made in early Spanish documents strengthen this argument. In the mid AD 1700s, Sedelmayr, for example, describes unpopulated stretches, or buffer zones, upstream and downstream from the core of O'odham settlements along the Gila River to protect themselves against the Apache (Dunne 1955). The aggregation across the landscape is also correlated with increased production of wheat (DeJong 2009; see below), but that increase in wheat production is likely a product of the aggregation, not the cause. Regardless, the aggregation of population to the center of the GRIC could have occurred for defensive or economic reasons and resulted in a population density increase, allowing for the creation of political structures necessary for an intensive irrigation system.

Development of a Tribal Government Necessary for Intensive Irrigation. Population growth and aggregation had important implications for tribal life and leadership during the AD 1700s. Numerous studies of prehistoric Hohokam irrigation systems indicate that a multi-village organizational system was needed to adequately distribute water and maintain and construct canals (e.g., Howard 2006; Woodson 2010). Without a cooperative organizational structure, this large-scale canal system would not have succeeded. Indeed, Woodson (2003) argues that the lack of an irrigation canal system when the Spanish first arrived was not due to a lack of knowledge of irrigation. He argues instead that low population density and the lack of a centralized tribal government restricted the ability of the O'odham to irrigate.

Prior to the aggregation, Kino observed no centralized authority above the village level in AD 1694 (Bolton 1919). By the mid AD 1700s, these new aggregated settlements along the middle Gila River created a centralized tribal authority, which had not been previously documented during the historic period (Bolton 1919; Ezell 1961; Winter 1973). It appears that this leader grew out of the previous position of "war chief," but the beginnings of this tribal leadership remain unknown. The creation of this position and a tribal council, however, indicates changing social relationships among the previously scattered rancherías. This centralized tribal authority, led by one man known as "Crow Head," organized the O'odham villages, and Winter argues, "that the growing need for cooperation necessitated by raiding, and possibly by irrigation, fostered the rise of the tribal leader and the tribal council" (1973: 74).

As Winter (1973) suggests, this centralization of leadership among the rancherías may have been instrumental in the adoption of irrigation among the historic villages, which is documented in historic observations at that time, and increased production of agricultural crops, by providing a framework of cooperation for developing more a complex agricultural system (Hunt et al. 2005). Thus, the creation of a tribal authority, possibly growing out of increasing population density from the aggregation of settlements, allowed for the creation of cooperative agreements for the successful management of a large-scale irrigation system.

The Growth of Intensive Irrigation and the Adoption of Wheat for a Market Economy. The use of new strategies to increase agricultural production is another key indicator of the intensification of land use. As argued in Chapter 2, land use frequently intensifies when subsistence farmers enter the market economy and begin cash cropping. Spanish documents provide important insights into agricultural production along the middle Gila River during the early historic period. While they do not provide specific quantities of harvested crops on a defined plot of land, their descriptions are essential to understanding how the intensity of agriculture practiced across the landscape changed during the historic period. During the historic period, these documents indicate that the O'odham went from cultivating maize, beans, and squash for subsistence purposes without large-scale irrigation (likely just using small ditches from the river) to cultivating sizeable tracts of wheat and, possibly, maize with large-scale, multi-village irrigation systems. Crops were sold to the Spanish and the Americans. All of these lines of evidence indicate that people did intensify agriculture throughout the historic period.

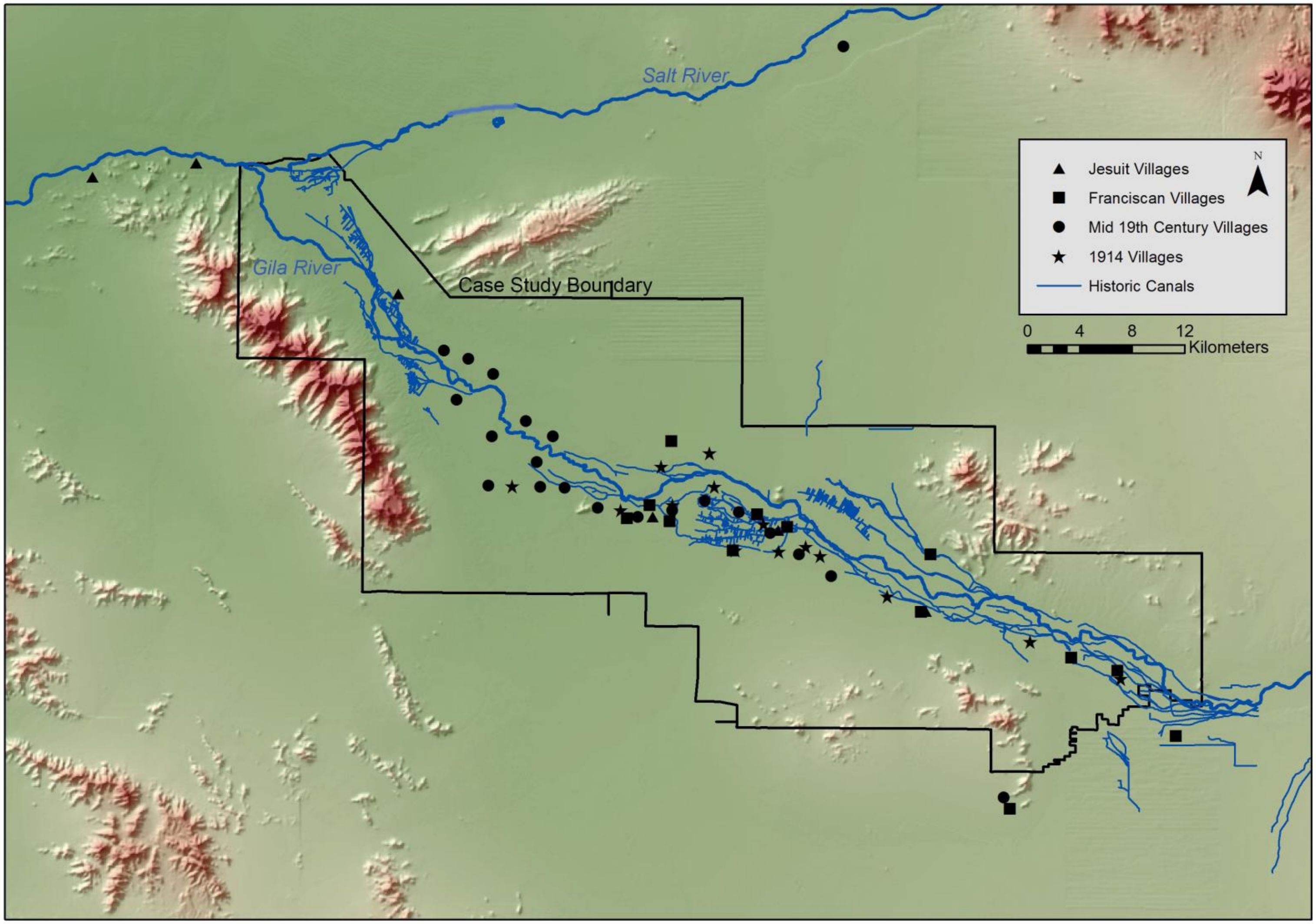


Figure 3.8: Map of Middle Gila River Historic Canals

The Loss of Water on the Middle Gila River (AD 1870– 1950) and Ethnographic Lessons about the Maintenance of Soil Quality along the Middle Gila River

After their agricultural and economic success of the mid AD 1800s, the O'odham faced a number of challenges that greatly decreased their agricultural productivity from the AD 1870s until today. With the influx of newcomers into the region and the reduction of the threat of Apache raiding, incoming American agriculturalists quickly settled the river upstream from where the O'odham were farming. These American farmers drew so much water off the river through their newly constructed irrigation canals that little water was reaching the GRIC by the AD 1870s (DeJong 2011; Southworth 1919). This drawing of water off the river upstream combined with a prolonged drought beginning in AD 1875 until 1883, resulted in the drastic reduction of available water, irrigated acreage, and bushels of wheat produced by the O'odham (DeJong 2009). DeJong (2011) notes eleven failed summer crops in a 12-year period (AD 1892-1904) and five failed winter crops in five years (AD 1899-1904). Bigler (2007) also documents a time of rapid environmental change along the Gila River, with more unpredictable streamflow patterns, decrease in water availability, and environmental degradation due to increasing mesquite harvest to substitute for lost crops, negatively affecting the operation of the irrigation canals constructed throughout the historic period.

Despite extensive reports of poverty and starvation in the early AD 1900s, it appears that the O'odham at least partially recovered in the decades following, planting hundreds of acres of fields adjacent to the middle Gila River (Castetter and Bell 1942; Ravesloot et al. 2009; Southworth 1919). In January of 1914, Clay Southworth undertook extensive mapping of agricultural fields along the middle Gila River and interviewed many of the older GRIC members to document agricultural strategies in preparation for the construction of the San Carlos Irrigation System (Southworth 1919). The maps created by Southworth provide a wealth of information that not only specifies the borders of each field area and the placement of canals and field furrows, but also what was growing in each of these fields. Many of these fields were mapped as growing grain – wheat and barley – while very few were growing maize, leading some to believe that the historic documentation is correct in that the transition to cash cropping wheat was almost complete at this time. These fields, however, were mapped in January – the heart of the wheat growing season – and do not depict what was grown in other months of that year.

In his interviews, Southworth (1919; DeJong 2011) documented the O'odham's desire and efforts to maintain agricultural production, despite little water reaching the GRIC at that time. For example, John Makil, who farmed acreage in the Casa Blanca District of the GRIC says, "There was plenty of water in the river all the year around. Indians got two crops a year; sowing wheat during the winter, melons, corn, pumpkins and other things, after we got off our first crop. We got our second crop in the winter." (DeJong 2011: 61).

John Head of the Casa Blanca reaffirms,

> There was plenty of water in the river the whole year through, before the white people diverted it. Indians had all they wanted in their ditches all the time. Had all kinds of crops, both grain, vegetables and plants. They were contented and prosperous. But when the white people took our water, we were left without any

> resources. We had to fall back on the seepage water, but it is not enough to keep us and families alive… (DeJong 2011: 93).

These interviews also provide extensive information about changes in soils quality following decreases in available water. O'odham elders mention that sodium and salt problems on the middle Gila did not exist until GRIC farmers lost the use of irrigation water to flush the fields of salts. With the loss of river water, they were forced to rely on well and seepage water, which they bemoan as having deleterious effects on the soil. James Hollen, working in the Gila Crossing area downstream of most GRIC fields, describes, "Seepage water is not desirable water to be used on account of the alkali it contains. It leaves a hard crust on top of the soil, and plants that are sensitive to it do not do well at all" (DeJong 2011: 92). Indeed, many of the maps that Southworth created designate wide swaths of land as being alkaline – a legacy that remains in many of the soils today (Miles 2013; Southworth 1919).

Interestingly, these farmers mention the various ways they had improved the soils with hard labor and the addition of sediments and water through irrigation – something that is lost with the use of well and seepage water. Multiple farmers interviewed by Southworth mention the "rough land" (DeJong 2011: 58, 59, 85) and the need for immense amounts of labor to level the land to make it arable. Cos-Chin, farming in the Santan area, provides insight into improving the soil, "As to fertilizing our farms, we do not have to use any fertilizer, soil is rich except in some districts where there is alkali, then flood water is needed to fertilize it" (DeJong 2011: 85). Russell reiterates, "The Pima knew, however, how to deal with this difficulty [alkaline soil] – they flooded the tract repeatedly and in this way washed the alkali out of it. They declare that they never abandoned a piece of ground because of it" (1908:87). Unfortunately, these strategies to sustain and improve the quality of soil throughout the historic period became unavailable as little water for irrigation reached the lands farmed by the Gila O'odham.

Gaps in Our Knowledge of the Agricultural and Economic Development Gila O'odham and the Ecology of the Middle Gila River

Extensive research done on the irrigation canals in the Phoenix Basin has provided solid evidence that canals were managed by communities organized at the scale of individual canal systems (each fed by a main canal off the river) prehistorically and that the agricultural areas themselves were likely managed at the household level (Henderson and Clark 2004; Howard 2006; Woodson 2010). This regionally uncentralized management system provides an excellent comparison to the mostly centralized Peruvian system (Chapter 4) and the highly centralized Mesopotamian and many modern irrigation systems (Chapters 2 and 7). Because the Hohokam irrigation system was used for over a millennium, the middle Gila River Valley also presents an opportunity to understand how long-term irrigation affects soils.

The effects of the intensification of agriculture can also be measured by comparing soils from prehistoric subsistence-based fields to historic cash-based agricultural fields. In this chapter, I argue that increases in population density, the creation of a political structure to allow for cooperative agriculture, and the adoption of a large-scale canal system and production of wheat indicate that the O'odham intensified agriculture throughout the historic period in order to meet the market demands. The initial aggregation of O’odham settlements and the introduction of new crops and technologies in the mid AD 1700s set a complex set of decisions into motion, including the creation of a tribal council, the expansion agricultural production, and the construction of new canals to open more acreage for farming. These adaptations resulted in the intensification of agriculture by the O’odham to meet market demands introduced by the Spanish and Americans.

This intensification of land use has important implications for soil quality of agricultural fields along the middle Gila River. While the historic documents are enormously helpful in reconstructing the social and economic adaptations of the O’odham, analysis of archaeological data is necessary to untangle the complexities of these changes in the O’odham agricultural system. Because previous research on other small-scale farmers across the world shows divergent effects of the intensification of agriculture on soil quality, archaeological sampling of these prehistoric and historic agricultural fields is needed to document not only the ecological effects of this historic transition, but also of long-term irrigation agriculture.

Chapter 4

PREHISPANIC CONTEXT OF THE NORTH COAST OF PERU AND THE PAMPA DE CHAPARRÍ

As a comparison to ancient irrigated fields in the Phoenix Basin, soil samples from prehispanic agricultural fields on the north coast of Peru were collected to understand how different environmental and social contexts affect the long-term sustainability of irrigated agricultural soils. The Pampa de Chaparrí, where the sampling for the Peruvian case took place, is located in the Lambayeque region of northern Peru and has diverse prehispanic agricultural fields dating from the Middle Sicán to Inka Periods (AD 900 – 1532) still visible on the surface (Figure 4.1). Samples were collected from a variety of field types to understand how the longevity and intensification of irrigation agriculture affected soil quality in this region.

Across coastal Peru, large-scale prehispanic irrigation systems have been the focus of study by archaeologists for decades. These irrigation canals have provided valuable information on the social control of water distribution (e.g., Farrington 1974; Farrington 1977; Farrington and Park 1978; Farrington 1983; Hayashida 2006; Kosok 1965; Moseley 1983; Netherly 1984; Ortloff et al. 1983; Ortloff 1993; Pozorski 1987), the relationships between El Niño and tectonic activity and the abandonment of irrigation systems (e.g., Dillehay and Kolata 2004; Fagan 2009; Moseley 1983; Moseley and Deeds 1982; Ortloff et al. 1982; Ortloff et al. 1985; Sandweiss et al. 2001), and the farming strategies of prehispanic communities (e.g., Erickson 2006; Netherly 1984; Téllez and Hayashida 2004). The agricultural fields, on the other hand, have been largely ignored in the archaeological record, as they have in the Phoenix Basin. Unlike the Phoenix Basin, however, the fields on the Pampa are highly visible on the surface, which is interesting for soil sampling because the different parts of the fields (i.e., irrigation furrows and their adjacent raised ridges) can be easily observed and tested. In addition to the longevity of irrigation on the Pampa, certain agricultural fields show evidence of state-level control, making it possible to evaluate the effects of different land use intensities on agricultural soils. Finally, archaeological and historic evidence indicate centralized, state-level control of the irrigation systems during the Chimú and Inka time periods, providing an interesting counterpoint to the community-based Hohokam irrigation systems. This chapter presents the environmental and cultural context for the irrigated fields that were sampled on the Pampa de Chaparrí and provides data concerning intensively used walled fields and irrigation management (Figure 4.2; henceforth referred to as the Pampa).

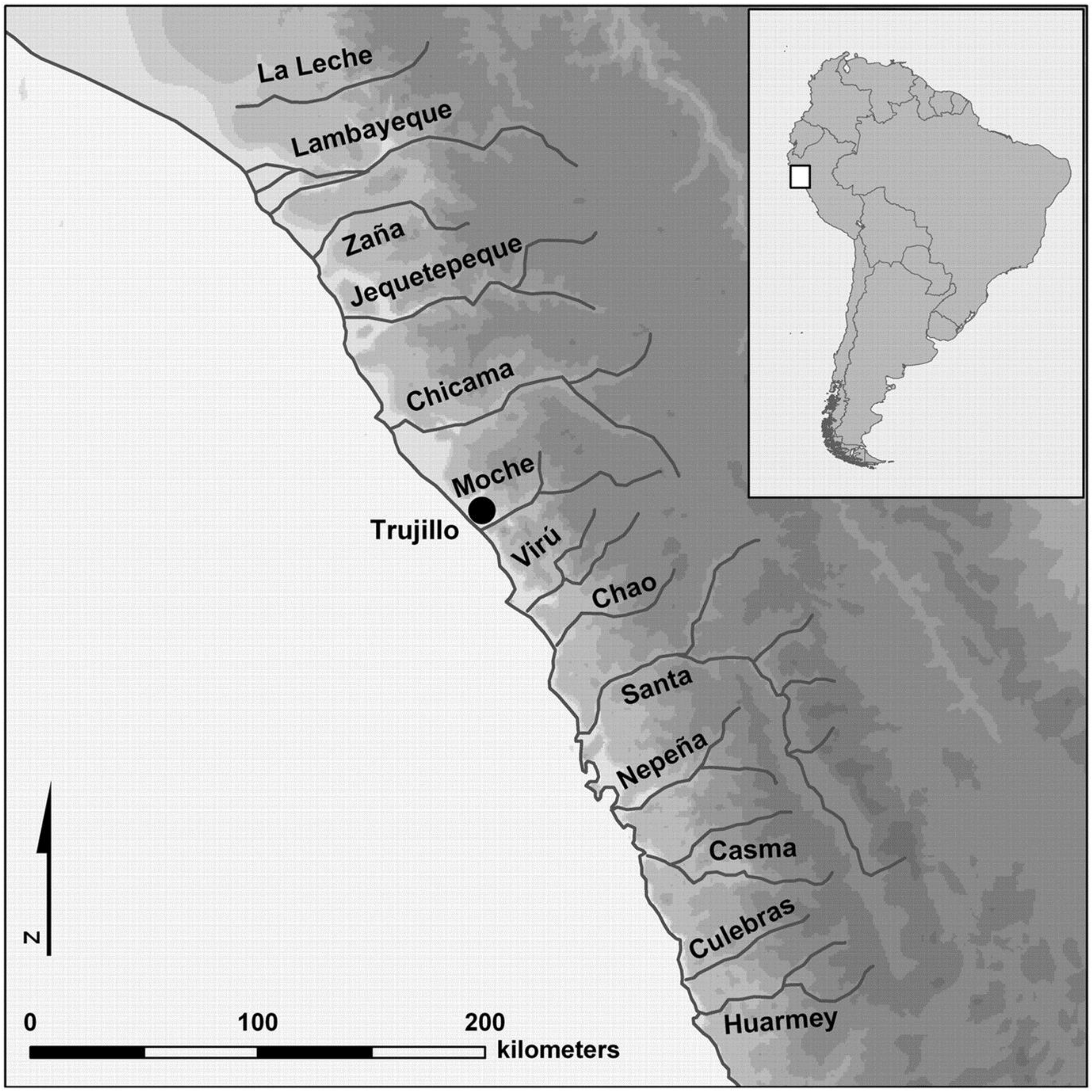


Figure 4.1: Map of Major River Valleys along the North Coast of Peru. The Pampa is located on the La Leche River Watershed. (Millaire 2010)

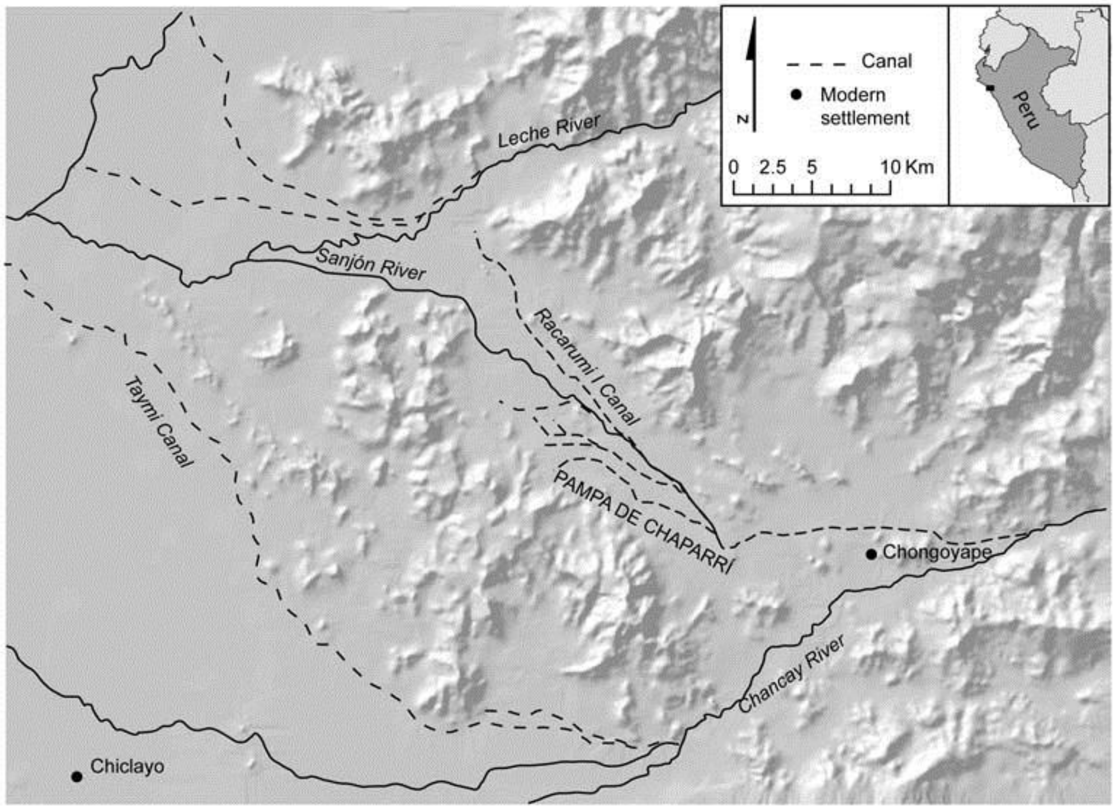


Figure 4.2: Map of the Pampa de Chaparrí

Environmental and Archaeological Background of the Pampa de Chaparrí

Environmental Context of the Pampa de Chaparrí

The Pampa de Chaparrí, located on the hyper-arid north coast of Peru, is bordered by the biologically productive Pacific Ocean to the west and the high elevation Andes Mountains to the east. The environment of coastal Peru is highly dependent on El Niño and La Niña cycles, caused by upwelling of warm and cold waters of the coast of Peru, respectively. The Pampa receives the majority of its rainfall during periods in which El Niño dominates the climatic regime (Waylen and Caviedes 1987). On average, the Pampa receives less than 3 cm of rain per year, with the exception of El Niño years, during which it receives much more rainfall (Nordt et al. 2004). As a result of this low rainfall, vegetation on the Pampa consists mostly of desert scrub and trees, primarily algarrobo (*Prosopis sp*.), zapote (*Capparis scabrida*), and vichayo (*C. avicennifolia*). While El Niño conditions bring much needed rain to agricultural fields in the region, the variability in both the timing and intensity of El Niño conditions can lead to destructive consequences for canal systems and this variation has been linked to the collapse of major civilizations on the north coast (Dillehay and Kolata 2004; Fagan 2009; Sandweiss and Solís 2009).

Like the Phoenix Basin, the rate of evapotranspiration of water, even during normal El Niño years, on the Pampa outstrips the average annual precipitation, necessitating the use of irrigation from perennial rivers to feed agricultural crops. The rivers along the north coast are fed by snowmelt and higher precipitation rates in the Andes Mountains. These rivers have provided the basis for the large-scale irrigation systems throughout the north coast of Peru and have supported highly complex societies that flourished for thousands of years prehispanically in the region. Important for the longevity of irrigation systems, the north coast of Peru is located on an active subduction zone, resulting in tectonic activity along the coast, which has also been blamed for the failure of many irrigation systems by drastically changing slopes upon which irrigation water flows (Chase 1992; Moseley 1983).

The Sanjón River, located at the foothills of the Andes Mountains drains the majority of the Pampa watershed (Huckleberry 2008; Huckleberry et al. 2012). The geomorphology is comprised of a mix of both older Pleistocene alluvial fans eroding from the Andes foothills and younger alluvial terraces that have been created from alternate downcutting and aggrading periods of the Sanjón River. Due to the lack of precipitation on this relatively young alluvial landscape, soil development is weak, frequently resulting in a thin A horizon, a weakly to moderately developed B horizon, and C horizon (Huckleberry et al. 2012; Nordt et al. 2004). Most of the prehispanic agricultural fields are located on the younger alluvial surfaces (Huckleberry et al. 2012; Nordt et al. 2004).

Previous Research on Agricultural Soils on the Pampa. While little research has been done on the prehispanic agricultural soils across the north coast of Peru, the Pampa has fortunately been subject to a preliminary study of soils that has helped clarify the characteristics of agricultural soils (Nordt et al. 2004.). This research has shown little evidence for salinization in the fields, but also low levels of nitrogen on cultivated soils, most likely requiring prehispanic inputs of nitrogen for the production of crops (Nordt et al. 2004). The agricultural soils are mostly coarse textured, allowing for good permeability and rapid infiltration of water, which prevents salt build up in the soils from irrigation (Nordt et al. 2004). Because much of the Pampa was farmed in the past, control samples were not located during sampling for this dissertation. Fortunately, during this study, Nordt and colleagues (2004) were able to collect landscape control samples from an adjacent valley to understand the anthropogenic impacts of irrigation agriculture on the Pampa that provide a baseline of expectations for unfarmed soil characteristics. Nordt and colleagues (2004) stress the need for further sampling across the Pampa to fully understand the impacts of prehispanic agriculture in this area – a gap that this project is designed to address.

Late Prehistory of the North Coast of Peru

Despite the backlash against Wittfogial thinking concerning the relationship between large-scale irrigation systems and the rise of complex societies, there is little doubt that the rise of prehispanic states on the north coast was related to the gravity-fed irrigation systems bringing much-needed water to fertile agricultural lands along the coast. While irrigation first emerged on the north coast of Peru around 5400- 6700 BP (Dillehay 2005), the irrigation systems on the Pampa de Chaparrí were not constructed until the Late Intermediate Period (A.D. 900 – 1450) during the middle Sicán period. These irrigation systems continued to be used through the Inka Period (AD 1450 – 1532) until abandonment shortly after Spanish conquest (Table 4.1). The following sections provide the cultural background of the North Coast and Pampa de Chaparrí during the main periods of occupation of the Pampa.

Table 4.1: Chronology and Major Cultural Events during the Occupation of the Pampa de Chaparrí Chronology (adapted from Hayashida 2006)

Period	**Associated Dates**	**Important Cultural Events**
Middle Sicán	AD 900 - 1100	Canal system constructed; RIIA and RIIC are main distribution canals
Late Sicán	AD 1100 - 1375	RIIB canal constructed, expansion of the canal system
Chimú	AD 1375 - 1460	Reorganization of settlements, RIIA-Upper abandoned
Inka	AD 1460 - 1532	Reorganization of settlements and management of irrigation canals
Spanish	AD 1532 +	Canal system abandoned, settlements relocate from the Pampa

		to the coast

Middle and Late Sicán Periods (AD 900 – 1375). The middle and late Sicán periods on the north coast of Peru, defined by Izumi Shimada, represented a cultural fluorescence after the collapse of the Moche Empire (Shimada 2000). Unlike the conquering Chimú and Inkan Empires (see below), the power of the Sicán State was focused solely in the north, taking advantage of resources, such as tropical shells, emerald amber, and mined goods, to trade to other areas as far as Colombia and Ecuador (Shimada 2000). During the middle Sicán Period, the absolute quantity and quality of material remains, including copper and gold alloys, monumental platform mounds, and beautiful art, are steeped in religious ideology that has received much archaeological attention. With their extensive specialization in metallurgy and crafts, the Sicán expanded their state-level religious polity (Shimada 1981, 1982). The Pampa de Chaparrí was likely occupied at this time to build upon great success in metallurgy, craft production, and extensive trade networks (Shimada 1990). With the power of the religious ideology, elites during the middle Sicán were able to mobilize labor to construct monumental architecture, including platform mounds across the north coast.

In AD 1100, the Middle Sicán state met an abrupt demise, as temples were burned, settlements abandoned, and religious iconography changed (Shimada 1990). Archaeological evidence indicates that there was a concerted effort to remove extant political and religious leaders throughout the north coast. Archaeologists have hypothesized that a severe, prolonged drought beginning in AD 1020 and lasting for 30 years may have contributed to the demise of the authority of the middle Sicán (Shimada 1990; Thompson and Mosley-Thompson 1985). The middle Sicán leadership could not ameliorate this change in natural conditions, and their religious power was likely undermined, leading to a drastic change in religion and leadership with the shift to the Late Sicán. Interestingly, despite the major changes to elite classes with this shift, many other people did not appear to be affected. Populations remained large and management of irrigation canals did not change at this time (Sandweiss 1995). The Late Sicán elites remained in power until the Chimú Empire conquered them in the mid to late AD 1300s in the Lambayeque region.

Chimú (AD 1375 – 1460) and Inka Period (AD 1460 – 1532). With the conquering of the Sicán State, the Chimú rapidly filled their power vacuum and, for the first part of the period, the Chimú greatly expanded the irrigation system throughout the north coast. The transition to the Chimú period represented a major change in settlement patterns and irrigation management across the north coast of Peru. Most of our knowledge about the Chimú comes from excavations from the seat of the Chimú Empire located at Chan Chan in the Moche Valley, approximately 200 kilometers south of the Lambayeque region, where the Pampa de Chaparrí is located (Kolata 1990; Moseley and Deeds 1982; Moseley and Day 1982).

During the early to mid AD 1000s (while the Chimú Period does not start on the Pampa until AD 1375, the Chimú obtained power in the Moche Valley earlier, and it should be stated that chronology of the beginning of the Chimú Period in the Moche Valley is dubious, at best, Shimada [2000]), the Chimú focused on expanding their agricultural land area, with the irrigation system on the north coast reaching its greatest extent at this time. The Chimú exerted control over irrigation systems (see more specific information below) and relied on surplus agricultural production to fund a rapidly expanding empire and elite class (Shimada 2000). The political and economic success of the Chimú resulted in extensive and impressive monumental architecture, including *ciudadelas* and *audiencias*, which housed royal families and were built with *mi'ita*, or non-resident forced labor (Keatinge and Day 1973; Willey 1953). Their agricultural success was short-lived, however, when the irrigation network collapsed throughout the region in the mid AD 1300s. The explanation of the collapse of the irrigation network has been subject of much debate. Moseley and Deeds (1982) stress that no evidence exists for endogenous causes, like loss of bureaucratic control or salinization, that might have led to the collapse of the system. Many archaeologists, however, have questioned the role of tectonic uplift destroying the grades upon which canals are dependent to accurately deliver water (e.g., Moseley and Deeds 1982; Ortloff et al. 1983). Others have found evidence for major El Niño flooding that may have destroyed headgates and major canals, after which the Chimú abandoned many canal systems (Pozorski 1987).

Whatever destroyed the canal systems along the north coast, the Chimú shifted their focus to expanding their military power and conquered north into the Lambayeque region and the Pampa de Chaparrí. At this time, the Pampa saw an increase in administrative control over roadways and canals, an influx of population, and the construction of new settlements and administrative centers. The Pampa represented an opportunity for the Chimú to take over Sicán trade routes and expand irrigated acreage to support their elite classes (Cabello de Balboa 1951). The Chimú then remained in power throughout coastal Peru until the Inka Empire conquered them in AD 1460.

Because the Inka occupation of the north coast of Peru was prematurely terminated by Spanish contact, little is known about Inka occupation of the Pampa. In fact, in most research, the Inka period is lumped into the Chimú Period, since archaeologically their material remains are similar on the north coast (Shimada 2000). Like the Chimú, the Inka exerted control over the north coast, through military power and administrative control over agricultural systems. Their political success was short-lived, however, with the entrance of the Spanish in the AD 1530s.

Spanish Period (AD 1532 +). With Spanish contact, major changes swept through the western hemisphere, and the north coast of Peru was not exempt from these changes. The Spanish decapitated Inkan political organizations, enslaved indigenous populations, and reorganized trade routes and irrigation systems (Alchon 2003; Hemming 2004; Sherbondy 1992; Zevallos Quiñones 1975). As the Spanish entered the region, they altered the distribution and allocation of water, and the Pampa de Chaparrí was not exempt from these changes. The Pampa was abandoned shortly after contact as the Spanish constructed new canals upstream of the Sanjón River, cutting off water to the Pampa (Hayashida 2006; Huckleberry et al. 2012).

Agricultural Fields on the Pampa de Chaparrí

On the Pampa, extensive archaeological research has been conducted over the last decade to understand the development of the irrigation system in this region and reflect the larger interpretations made concerning irrigation management on the north coast of

Peru. Comprising one of the largest canal systems in the region, the agricultural fields on the Pampa de Chaparrí were fed by a large intervalley canal, the Racarumi I Canal (RI) (Kosok 1965). The RI canal connects the Chancay River with the Leche River, flowing through the Pampa adjacent to the Sanjón River. At over 50 km long, the RI fed three large distributory canals on the Pampa - the Racarumi IIA, IIB, and IIC – all initially constructed during the middle Sicán Period (Figure 4.3, Hayashida 2006).

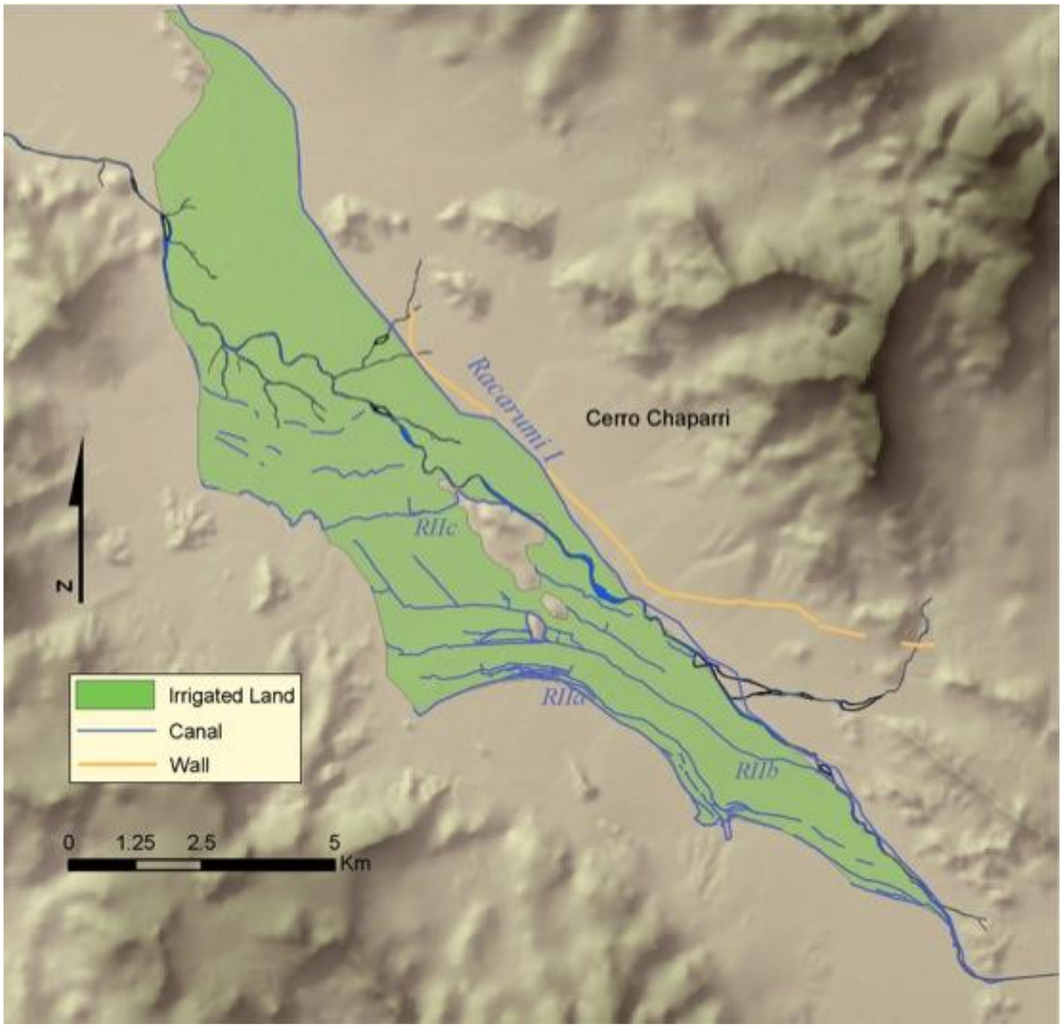


Figure 4.3: Map of Major Canals Along the Pampa de Chaparrí

Because the Pampa was abandoned shortly after Spanish conquest (Hayashida 2006; Huckleberry et al. 2012), well-preserved agricultural fields remain visible on the surface and can be sampled to address the research themes of this dissertation (Figures 4.4 and 4.5). The agricultural fields, covering approximately 5400 hectares, constructed across the Pampa are highly variable in their patterning (Figure 4.6) with some fields being “comb-shaped” with arms of ridges of the raised field beds reaching downslope, while other fields are simply straight lines of ridges and furrows connecting larger, distributory canals (Nordt et al. 2004). These differences in field patterning could be indicative of optimization for specific crop growth or topography, organizational differences, or specific farmer preferences, and may have had differential effects on the quality of the soil.

Figure 4.4: Example of a Prehispanic Agricultural Field on the Surface of the Pampa de Chaparrí

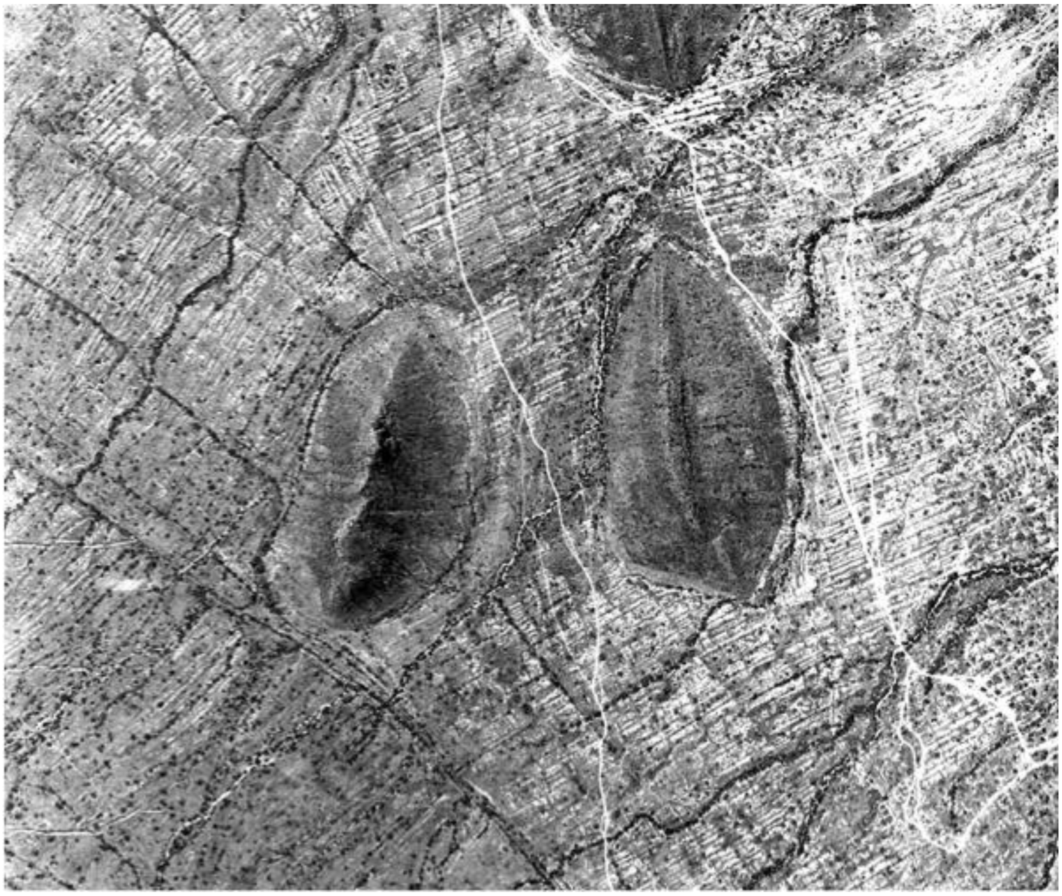


Figure 4.5: Aerial Photograph of Agricultural Fields on the Pampa de Chaparrí

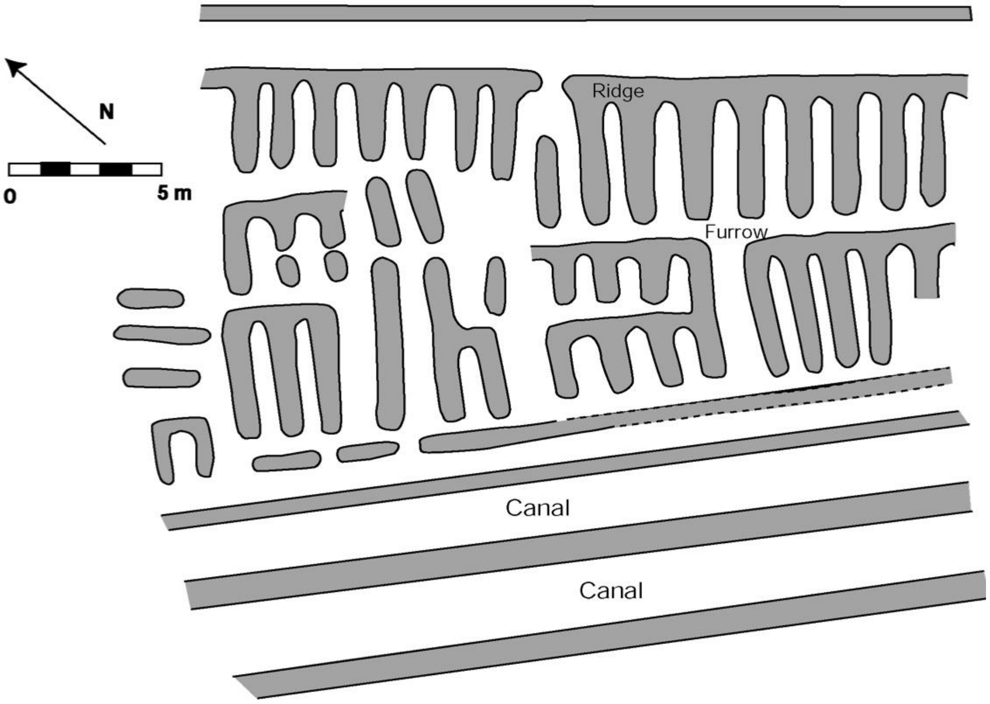


Figure 4.6: An Example of a Prehispanic Field on the Pampa de Chaparrí, illustrating the variability in ridge and furrow organization (Nordt et al. 2004)

Prehispanic farmers on the north coast of Peru farmed with furrow irrigation, in which a small field lateral canal (referred to in this dissertation as a furrow) is excavated and the excavated dirt is used to create an adjacent ridge to deliver water from larger canals to the growing surface (Erickson 1992). This strategy results in a thicker A horizon on the ridge allowing for a deeper rooting zone for agricultural crops. Personal observation of traditionally managed fields in the same region as the Pampa indicates that different crops were planted across both the ridge and the furrow. For example, maize was planted in the furrows, while squash and beans were planted along the sides of the ridge and allowed to crawl over ridges (Nordt et al. 2004; Figure 4.7). Prehispanic crops were highly diverse and included maize, cotton, squash, gourds, beans, peanuts, potatoes, avocado, and guava.

Figure 4.7: Photo of a Modern Traditionally Managed Field near the Pampa de Chaparrí.

The Intensification of Agriculture within the Walled Fields on the North Coast of Peru

With the transition to centralized, state-controlled management of the irrigation systems during the Chimú period, archaeologists have found evidence that the Chimú Empire attempted to intensify agriculture in the Pampa and other valleys across the north coast of Peru. Like on the Pampa, Chimú administrative sites were relocated to highly productive valleys, like the Santa and Jequetepeque Valleys, to oversee agricultural production and irrigation canals. Archaeologists argue that this shift in administrative centers to fertile agricultural lands indicates a shift in state administrators taking a direct interest in the control of irrigation canals and agricultural fields (Dillehay and Kolata 2004; Hayashida 2006; Wilson 1988). This intensification of agriculture likely took place to produce a predictable surplus in order to support the expanding Chimú Empire. Perhaps the most highly visible effort to intensify agricultural production during the Chimú Period was the construction of large, walled fields at the Chimú capital of Chan Chan and on the Pampa de Chaparrí (Hayashida 2006; Kolata 1990; Téllez and Hayashida 2004). These walled fields are rare constructions on the north coast of Peru, likely indicating their importance to agricultural state production. Walled fields were first noted on the north coast at Chan Chan, where they were constructed and farmed within the walls of citadels (Kolata 1990; Moseley and Day 1982). Historic documents also mention walled fields in the Moche Valley, which were dedicated to Inca Huayna Cápac (the 11th emperor of the Inkan Empire) and devoted to the cultivation of coca (Netherly 1988). This archaeological and historic evidence indicates the importance of these walled fields and the likely control that state administrators had over their use to support state-level bureaucrats and elites.

Figure 4.8: Picture of the Adobe and Masonry Wall Surrounding One of the Sampled Fields on the Pampa de Chaparrí

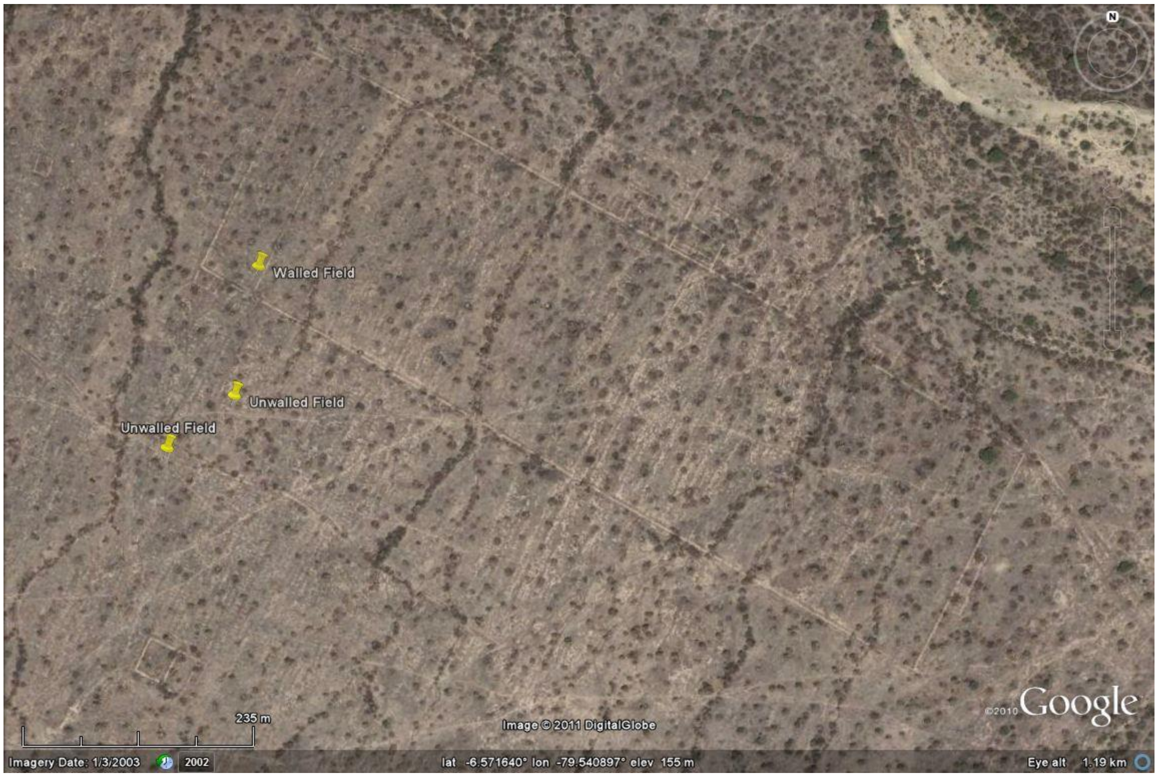


Figure 4.9: Satellite Image of One of the Walled Fields on the Pampa

Four walled fields, constructed of adobe and masonry, ranging from 0.8 to 21 hectares in area (see Figures 4.8 and 4.9), were located during archaeological survey of the Pampa (Hayashida 2006; Téllez and Hayashida 2004). Clear irrigation agricultural features, including field canals, ridges, furrows, and intakes are enclosed within these walls, indicating that these walled enclosures were used for agricultural production. Téllez and Hayashida (2004) argue that the amount of labor necessary to construct these huge architectural features likely indicate that labor was likely organized and demanded by elites from farmers.

These walled fields provide an opportunity to test how the intensification of agriculture affected soil quality on the north coast of Peru. Numerous examples in antiquity show how various states and empires have intensified agriculture in order to support elites and bureaucrats, including the Tarascan Empire, Hawaiian chiefdoms, and Mesopotamian states (Adams 1978; Fall et al. 2002; Fisher et al. 1999; Kirch 1994; McCoy and Graves 2010; Rosen 1997; Wilkinson and Christiansen 2007). We have clear archaeological evidence that the Chimú did the same and not only exerted control over irrigation systems but made efforts to intensify agriculture in highly productive valleys and within walled fields.

Gaps in Our Knowledge of the Irrigated Agricultural System on the North Coast of Peru

Like the Phoenix Basin, extensive archaeological research has been done to address questions concerning the structure of irrigation canals and their essential resource – water. These studies have clarified how irrigation water and agricultural fields were likely managed differently during transitions to various empires across the north coast of Peru. The level of centralization of the management of irrigation changed through time as power shifted from the Sicán to Chimú and Inka Empires. It is unknown, however, how this change in irrigation management affected the sustainability of the irrigation system and its associated agricultural fields.

The preservation of the prehispanic landscape on the Pampa is unparalleled on the north coast of Peru, allowing for the sampling of soils from agricultural fields to understand how the intensification and longevity of irrigation altered the quality of soils in this region of the world. Because these fields were farmed for over 600 years, the effects of long-term irrigation agriculture on soil quality can be explored. Additionally, the intensification of agriculture likely occurred within the walled fields, providing a context to understand how soils in intensively used within state-controlled fields compared to other agricultural areas.

The north coast of Peru also makes for an interesting comparison to the other case study explored in this dissertation – the middle Gila River. While the middle Gila River was largely organized by canal system, irrigation canals on the Pampa, at least during the Chimú and Inka periods, were managed by centralized state control. During times when irrigation management was less centralized, like during the Sicán Period, households still needed to produce a surplus to support an elite class. Thus, by comparing how soils were affected under these different irrigation management regimes, interpretations can be made concerning the relationship between the longevity and intensification of irrigation systems.

Chapter 5

METHODS FOR SAMPLING AND ANALYZING SOILS FROM ANCIENT AGRICULTURAL FIELDS

The previous chapters introduced the gaps in our knowledge concerning the impact of the irrigated agricultural systems on soil quality in southern Arizona and coastal Peru. This dissertation is designed to address some of those gaps and understand how these prehispanic irrigation systems can inform the development of sustainable irrigation agriculture today. This chapter introduces the innovative methods created to answer questions concerning how the longevity and the intensification of irrigation agriculture affected soil quality. In particular, this chapter details the sampling agreement with the GRIC-CRMP, the methods used to identify and sample prehistoric and historic agricultural fields in the Phoenix Basin and coastal Peru, the collection of soil samples, and the laboratory analyses used to process the soil samples.

The Identification and Sampling of Fields

North Coast of Peru

The excellent preservation of irrigated agricultural fields on the Pampa de Chaparrí on the north coast of Peru provided an opportunity to develop a methodology to sample ancient irrigated fields, which are rarely located in archaeological contexts. Irrigated agricultural fields on the Pampa were abandoned soon after Spanish contact (Hayashida, 2006; Huckleberry et al. 2012; Zevallos Quiñones 1975), and the landscape has been little used and manipulated since abandonment, resulting in a well-preserved archaeological context for sampling. Because little research has been done on soil fertility in abandoned irrigated agricultural fields, the Peruvian study was particularly important for developing this methodology and to determine the most productive laboratory analyses for irrigated soils, such as those that indicate salinity levels, for future, more complex sampling on the GRIC.

During May and June of 2009, soil samples were taken across the Pampa de Chaparrí from a wide variety of preserved prehispanic fields. Agricultural field areas were identified through a combination of previous archaeological survey, aerial photographs, and satellite images. In each identified field area, a 2 by 2 meter pit was excavated, and the soil horizons were mapped and characterized (Schoeneberger et al. 2012). Samples were collected from each horizon identified. Soils were generally very shallow and weakly developed, with a thin A horizon and a weakly developed B horizon, which likely developed due to anthropogenic inputs of water from irrigation agriculture (Huckleberry et al. 2012; Nordt et al. 2004). Generally, pits only had to be excavated approximately 20 to 30 cm until the C horizon was encountered.

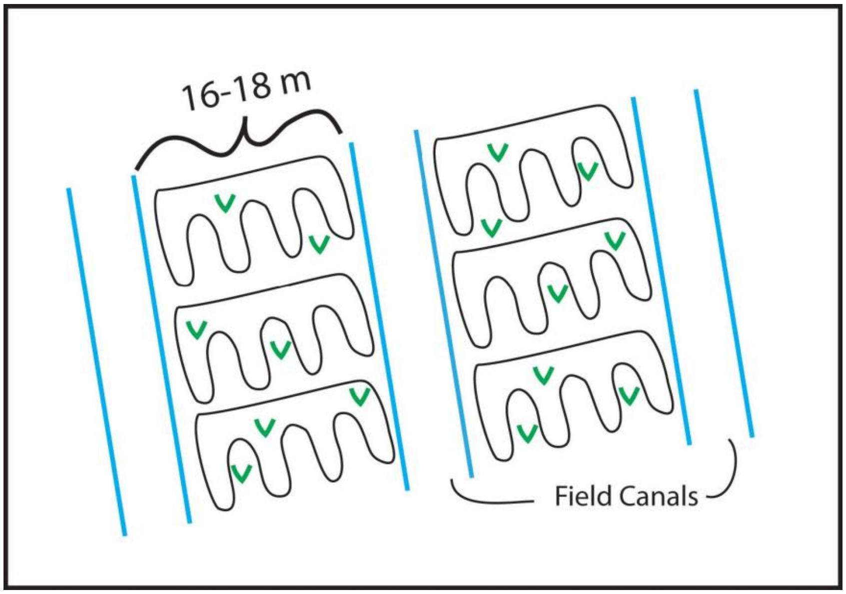


Figure 5.1: Example Layout of a Field on the Pampa

Because the ancient fields were identifiable at the surface, surface samples (0-10 cm in depth) were collected every five meters away from the excavated pit until approximately 20 samples were collected from each field system – a number that has produced statistically significant results in previous soil studies (Sandor, personal communication). Ten samples were collected from the furrows and an additional ten samples were collected from the ridges of the raised field beds. Ridges and furrows were delineated based on height or soil color differences (Figure 5.1). The sampling strategy adopted for the Pampa also provided an opportunity to compare differences between more and less intensively used field types (e.g., walled and unwalled fields) and to identify strategies that could have maintained or enhanced soil quality under long-term irrigation agriculture. In total, eleven different field areas were sampled across the Pampa, resulting in the collection of 253 soil samples (Figure 5.2).

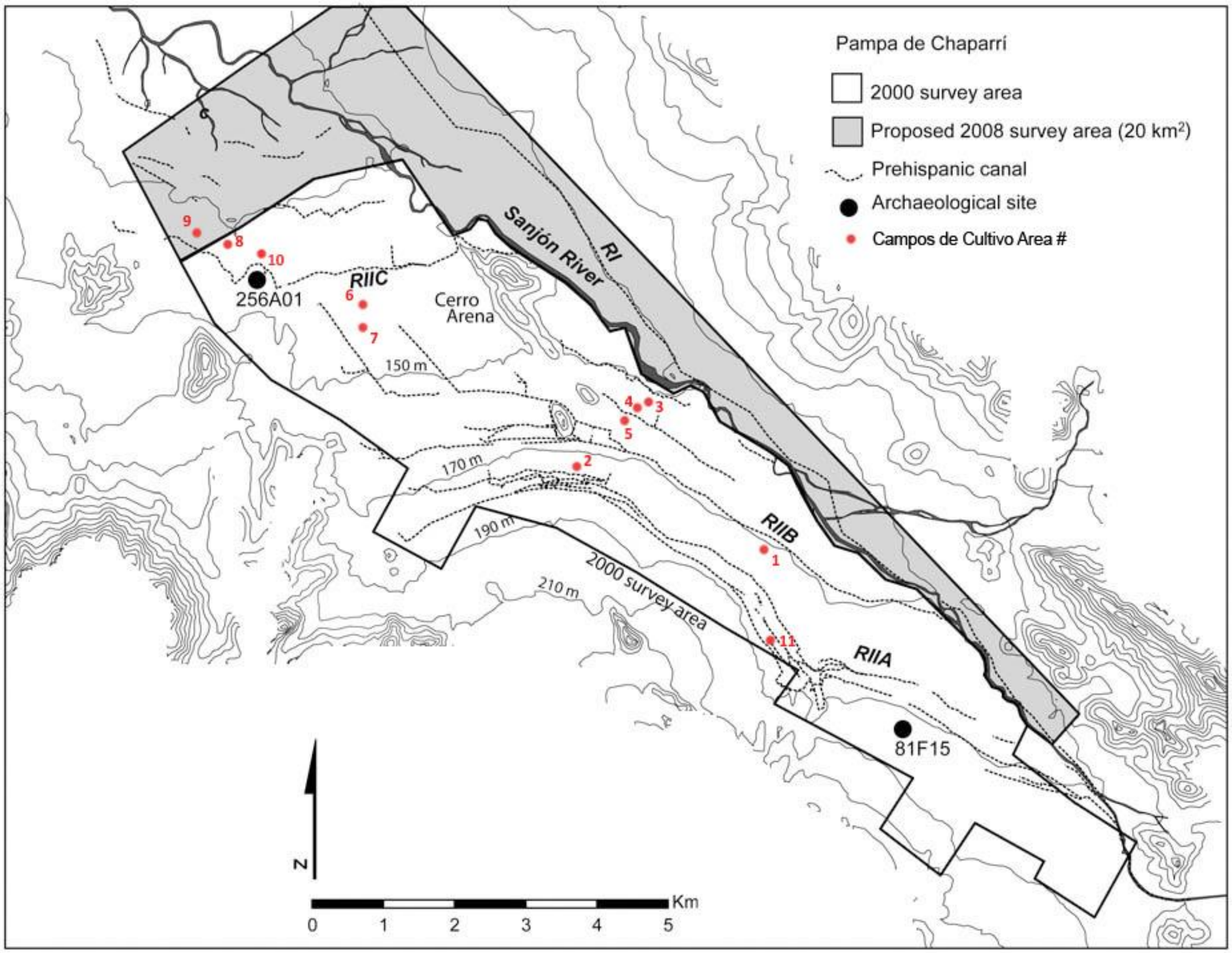


Figure 5.2: Sampled Sites on the Pampa de Chaparrí

Table 5.1: Characteristics of Ynalche Field Sites

Field Area Number	Field Area Name	Why Important to the Research?	Geomorphic Context (adapted from Huckleberry et al. 2012)
N/A	Anthropogenic Deposit	Buried anthropogenic deposit, only 2 samples collected	Qru3 - Youngest alluvial fan surface (Huckleberry 2008)
1	Comb-Shaped Fields 1	Well-preserved fields	Qru1 - Young alluvial fan surface (Huckleberry et al. 2012)
2	Comb-Shaped Fields 2	Well-preserved fields	Qru1 - Young alluvial fan surface (Huckleberry et al. 2012)
3	Walled Field 1	Walled fields have been argued to have been managed directly by the state (Tellez and Hayashida 2004; Kolata 1990)	Qru1 - Young alluvial fan surface (Huckleberry et al. 2012)
4	Outside of Walled Field 1	Fields directly south of walled fields that were likely not under the direct control of the state	Qru1 - Young alluvial fan surface (Huckleberry et al. 2012)
5	Outside of Walled Field 1	Fields directly south of walled fields that were likely not under the direct control of the state	Qru1 - Young alluvial fan surface (Huckleberry et al. 2012)
6	Well-Preserved Fields 1	Well-preserved fields	Dissected Alluvial Fan (Nordt el al. 2004)
7	Well-Preserved Fields 2	Well-preserved fields	Dissected Alluvial Fan (Nordt et al. 2004)

8	Outside of Walled Field 2	Fields directly west of walled fields that were likely not under the direct control of the state	Distal End of Alluvial Fan (Nordt et al. 2004)
9	Waffle Gardens	Heavy buildup of silts in these fields, thick A Horizon	Distal End of Alluvial Fan (Nordt et al. 2004)
10	Walled Fields 2	Walled fields have been argued to have been managed directly by the state (Kolata 1990; Tellez and Hayashida 2004)	Distal End of Alluvial Fan (Nordt et al. 2004)
11	Sicán Fields	Fields were abandoned after the late Sican Period, providing an interesting counterpoint to other, more long-lived fields	Qrl2 (Huckleberry et al. 2012)

The Middle Gila River

Sampling the fields on the middle Gila River proved to be much more complicated than on the north coast of Peru. Because of the continued use of the middle Gila River landscape into modern times, prehistoric and historic agricultural fields have been buried and possibly altered by human and natural activity over the past centuries, including farming and alluvial deposition. This palimpsest of prehistoric, historic, and modern agricultural use necessitated the consideration of many additional factors to ensure that the signature of irrigation use in the prehistoric and historic fields was detected in the soil analysis.

Through limited sampling in 2004 on prehistoric and historic agricultural fields at the GRIC, Sandor (2010) developed a preliminary methodology for sampling these fields and identified areas where more research was needed. Surface samples from two irrigated agricultural fields – one prehistoric field and one historic field – were collected with a procedure similar to that followed on the Pampa, and Sandor and Strawhacker completed laboratory analysis for most of the characteristics important to understanding agricultural soil quality. The soils data from these two fields were included in this dissertation; Sandor's sampling technique provided the method for the sampling of other areas described below.

In order to collect data from preserved prehistoric and historic agricultural fields along the middle Gila River, I worked in collaboration with the Cultural Resource Management Program at the Gila River Indian Community (GRIC-CRMP) for this research. The sample collection largely operated under the umbrella of the Pima-

Maricopa Irrigation Project (P-MIP), which is a federal project currently researching and preparing the GRIC landscape for the construction of hundreds of miles of irrigation canals and the introduction of hundreds of thousands of acre-feet of water onto agricultural fields. Archaeologists at the GRIC-CRMP have been undertaking widespread testing of areas of new construction and current and future agricultural fields, which involves the excavation of thousands of backhoe trenches. It is these trenches that provided the opportunity to conduct subsurface documentation of agricultural fields and to collect sediments from prehistoric and historic fields. Due to restrictions by the GRIC, I could not select and excavate sampling areas. P-MIP’s backhoe trenches, however, exposed numerous ancient agricultural fields appropriate for sampling.

Trenches appropriate for sampling were initially identified based on the presence of agricultural features (including canals) that indicated adjacent sediments were likely farmed in the past (Table 5.2). After an agricultural feature was located in a trench, prehistoric and historic fields were identified through a suite of archaeological, historical, geological, and ecological data. The irrigated field deposits are frequently higher in organic matter and finer sediments (clays and silts) than non-field locations due to the influx of irrigation water that introduced new sediments and organic matter. These irrigated deposits created an anthropogenic horizon indicative of past cultivation that was then sampled for soil. Areas that did not have a diagnostic layer indicative of field deposits were not sampled.

Table 5.2: Soil Criteria for Identifying Buried Agricultural Fields along the middle Gila River

Soil Property for Identifying Fields	**Criteria for Recognizing Irrigated Fields**	**Significance for Previous Irrigation**
Soil Structure	Finely stratified (laminated) and/or Finer Sediments (clays and silts) compared to other horizons	Water movement typically deposits sediments in laminations. Irrigation water also introduces finer sediments to the system.
Soil Color	Darker colors compared to surrounding horizons	Irrigation water introduces organic matter to the system, resulting in darker soil colors.

In order to sample appropriate trenches, I relied on GRIC-CRMP project directors and archaeological crewmembers to alert me to possible sampling opportunities. After extensive pilot research on the GRIC, I identified the characteristics of an ancient agricultural field – buried (sometimes surface) horizon, with darker soil color and a laminated, finely stratified structure in the presence of another agricultural feature, such as a canal (Table 5.2) – and trained archaeological crewmembers of the GRIC-CRMP to identify potential prehistoric and historic fields. When crewmembers observed these characteristics, I traveled to GRIC to ascertain whether the feature was indeed an agricultural field and, if so, documented field observations and collected soil samples.

During field collection, agricultural fields (i.e., deposits that were watered by canals) were identified and mapped in the trench. Soil characteristics important for understanding the formation of the soil horizons, like texture, color, and pH, were recorded in the field (Schoeneberger et al. 2012). In order to assign a date to the buried fields, associated features, artifacts, and previously acquired OSL dates from the canals are used to date adjacent fields. Many of the canals, both prehistoric and historic, have been mapped and dated through extensive testing by the GRIC-CRMP (Woodson 2003, 2010).

Similar to the sampling procedure in Peru, soil samples were collected in a vertical column from every described horizon in the profile to identify the important characteristics of the soil, including soil age and formation factors (Schoeneberger et al. 2002). Then, soil samples were collected every 5 meters horizontally along the trench (and other adjacent trenches, if available) from the identified stratum of past cultivation, allowing for an evaluation of intra-field variability in soils and the collection of enough samples for statistically significant results. Nineteen different field areas – nine prehistoric and ten historic fields –were sampled, and 15-20 soil samples from each field were collected, depending on the length of the open trench and characteristics of the field deposits. All of the sampled field areas are explained in detail in Appendix A (Figure 5.3)

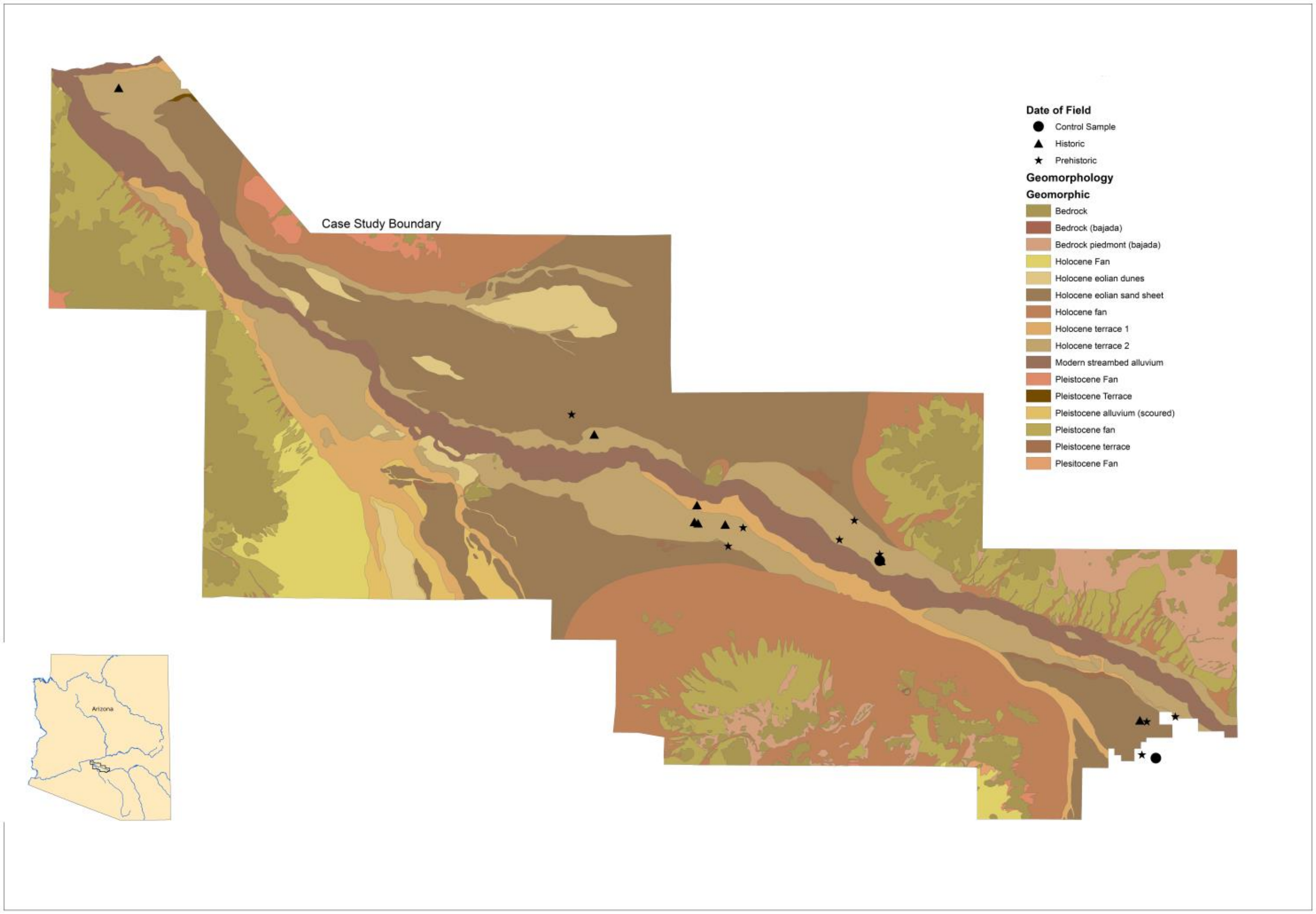
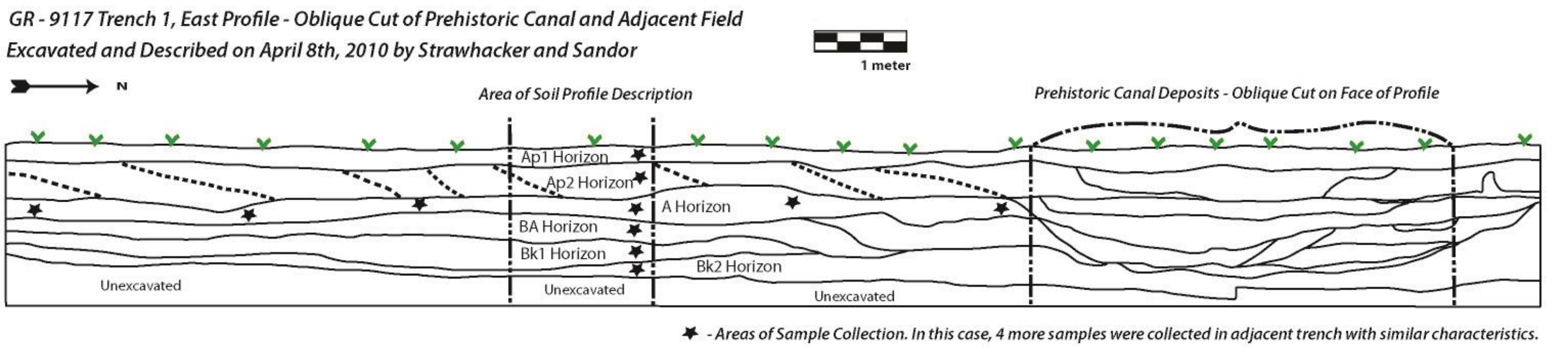


Figure 5.3: Sampled Sites along the Middle Gila River

Generally, prehistoric and historic fields were sampled in approximately one out of every five trenches assessed during fieldwork. Control samples, when available (N=10), were collected to compare soils from agricultural contexts to those from unfarmed areas. Areas of potential control samples were identified in two ways. First, areas with no prehistoric or historic canals or features that were in the same geomorphic context as identified fields were sampled to compare to the cultivated areas (see Sandor et al. 1990a for a description and justification of this method in a dryland system). Second, control samples were taken in contexts that were clearly not farmed, like an area found at site GR-9117 where a prehistoric field stratum was identified and sampled.

Site GR-9117 (Figure 5.4) contained a prehistoric agricultural deposit in a trench that was sampled for this research. A large prehistoric canal was located in this trench, making the presence of prehistoric fields likely. In an adjacent trench, a small field lateral, which directly fed water to the fields, ran perpendicularly to the large canal (Masse 1981; Woodson 2003 for descriptions of canal hierarchy). Dark, organic soil, high in fine sediments like clay and silt, was present below the surface and adjacent to where the canal fed the agricultural fields in the past (see A Horizon, Buried Prehistoric Field in Figure 5.4). Because of the characteristics of the soil profile and the proximity to the canal (both horizontally and vertically in the profile), this stratum is interpreted as a prehistoric field surface. The stars in Figure 5.4 note where samples were collected in both a horizontal row (to analyze the agricultural field stratum) and vertical column (to understand the development of the entire soil profile).


GR - 9117 Trench 1, East Profile - Oblique Cut of Prehistoric Canal and Adjacent Field
Excavated and Described on April 8th, 2010 by Strawhacker and Sandor

★ - *Areas of Sample Collection. In this case, 4 more samples were collected in adjacent trench with similar characteristics.*

Ap1 - Massive, cloddy, slightly hard, friable, brown (7.5 YR 6/3 dry) Sandy Clay Loam (22% clay), violently effervescent - **Anthropogenic cut and fill of canal, surface disturbance**

Ap2 - Massive, slightly hard, friable, brown (7.5 YR 6/3 dry) Sandy Clay Loam (22% Clay) with large chunks of carbonate, strongly effervescent - **Anthropogenic cut and fill of canal (see diagonal lines indicating oblique cut of canal)**

A - Massive, slightly hard, friable, dark brown (7.5 YR 5/3 dry), Loam (23 % Clay) with fewer gravels than horizons above, strongly effervescent - **Prehistoric field surface due to relationship to canal, finer sediments, and depth of clay and organic matter**

BA - Massive, slightly hard, friable, brown (7.5 YR 6/3.5 dry), Loam (23% Clay), strongly effervescent - **Transitional B horizon from A horizon above.**

Bk1 - Massive, soft, very friable, brown (7.5 YR 5/4 dry), Sandy Clay Loam (21% Clay), violently effervescent - **B horizon with pedogenic accumulation of carbonates**

Bk2 - Massive, slightly hard, friable, brown (7.5 YR 5/4 dry), Sandy Loam (13% Clay), violently effervescent - **B horizon with pedogenic accumulation of carbonates**

Figure 5.4: Sampled Areas of Trench 2 of GR-9117

Control samples were also collected from a trench at GR-9118, a site approximately 500 meters from GR-9117 and in the same geomorphic context. This trench exposed three large prehistoric distributory canals. These distributory canals do not directly feed fields but transport water to smaller canals and field laterals (Masse 1981; Woodson 2003). Because three of these distributory canals are located in one 25-meter trench, this area most likely did not operate as a prehistoric field, but instead served as an area where canals were excavated and maintained in the past (Figure 5.5). Thus, samples were collected in between these distributory canals from A horizons that have not been disturbed by modern activity to compare against the cultivated soil samples.

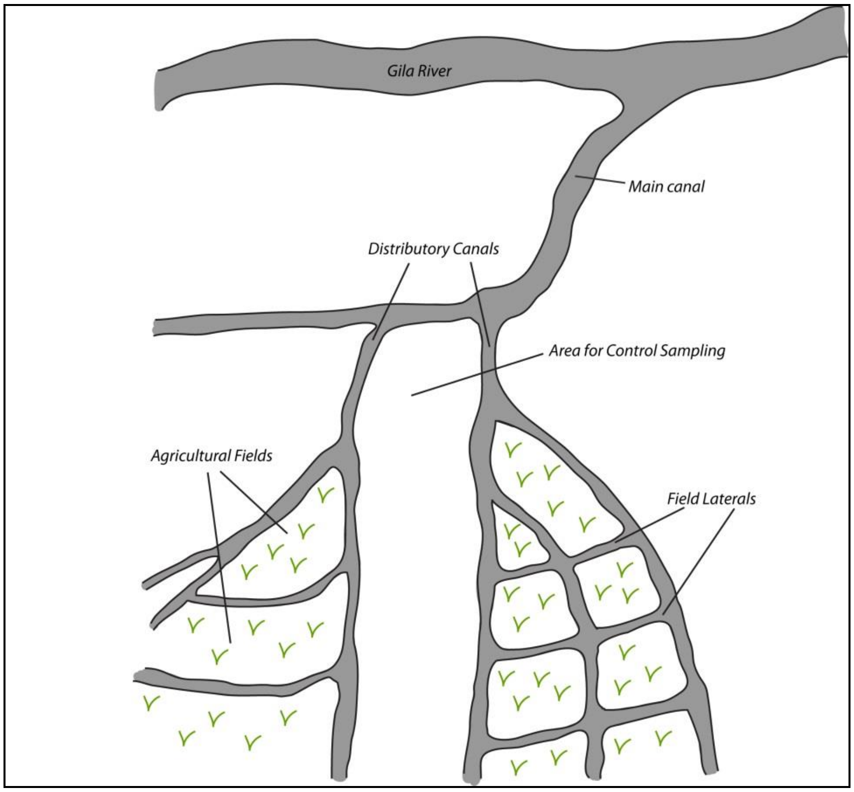


Figure 5.5: Irrigation Canals and the Selection of Control Samples (adapted from Plog 2008)

Prehistoric and historic fields are also located on the ground surface. Surface fields were identified through the association of abandoned prehistoric and historic canals at the surface and other archaeological and historic features and artifacts. For example, a historic field at GR-931 was located on the surface near the Old Stotonick Canal. This agricultural area is argued to be a historic field due to its proximity to the Old Stotonick Canal (used in the mid 1800s), its presence on Southworth’s 1914 agricultural survey maps, (Southworth 1914; Southworth 1919; Woodson 2003; see Figure 5.3 and Table 5.3), and the ubiquity of mesquite stumps at the surface (Figure 5.6). The presence of mesquite stumps indicates that the area had been cleared for agriculture by hand with an axe and not farmed since the introduction of the industrial plow in the 1950s (Wilson 1999) and thus, the surface deposits have not been affected by modern farming. The same method of sampling that was used for buried fields was used for surface fields, similar to the fields on the Pampa and Sandor’s (2010) pilot study. The soils in the excavated trench were characterized, and field samples were collected from the surface horizon. Table 5.3 lists all of the sampled sites and relevant characteristics for comparing their soil results.

Figure 5.6: Photograph of Mesquite Stumps at the Historic Agricultural Field at GR-931

Table 5.3: Characteristics of Sampled Sites Along the Middle Gila River

Field Site	Age of Sampled Agricultural Fields	Sample Numbers	Feature Number	Surface or Buried?	Modern Farmed Surface?	Geomorphic Setting and Age	Time of Last Agricultural Use	Degree of B Horizon Development
GR 738 – Reed 1 Field (2010.12x1)	Prehistoric (although historic canals are present)	140 - 161 (controls), 162 - 183 prehistoric field	None assigned	Buried	Currently cleared, but fallow	Holocene Terrace	Within the last 5 years	Well-developed
GR 1055 - C. Martinez Homesite (2010.01x10)	Historic	6-24, 90-103	Feature 33	Buried	Lawn area for a house.	Pleistocene Terrace	Approximately 1950	Well-developed
GR 9117 and 9118 – Pima Lateral Sites (94.14x31)	Prehistoric and Control Samples	25 - 62	Features 9 and 10	Buried	Recently harvested cotton field.	Pleistocene Terrace	Currently farmed.	Well-developed
		63 - 82	GR 9118 - None					
GR 931H – Old Mount Top Canal (SCIP Canal 13 access road	Historic	104 - 131	None assigned	Surface	No	Holocene Terrace	Before 1950.	Weakly developed

94.14x39)								
GR 643 - Parsons 6 Field (2011.12x 3)	Prehistoric	240-254	Feature 4	Buried	No	Holocene Terrace	Before 1950	Well-developed
GR 643 - Parsons 6 Field (2011.12x 3)	Historic	255-265 (controls) , 266-276 (historic field)	Feature 11	Buried	No	Holocene Terrace	Before 1950	Well-developed
GR 1530 - D-Johnson 4 Field (2011.12x 1)	Prehistoric	216-230	Feature 4	Buried	No	Pleistocene Terrace	Before 1950	Weakly developed
GR 1532 - D-Johnson 6 Field (2011.12x 4)	Historic	277-291	Feature 5	Buried	No, Fallow from a decade or two ago	Pleistocene Terrace	Within 2 decades	Weakly developed
GR 1528 - Bapchule Canal Site (L. Thomas Homesite	Historic	200-215	Feature 4	Buried	Cleared Area from nearby house	Holocene Terrace	Before 1950.	Well-developed

2010.02x16)								
GR-1157 Locus KK (Sandor Snaketown Samples 94.14x24)	Prehistoric	437-455	None assigned	Buried	No	Pleistocene Terrace	Prehistoric (Classic period)	Well-developed
GR-919 (Sandor Snaketown Samples 94.14x24)	Historic	456-475	None assigned	Buried	No	Holocene Terrace	Approximately 1940	Well-developed
GR 9127 - Diablo Sand & Gravel (94.14x42)	Prehistoric	350-361	Feature 2	Buried	Yes	Holocene Terrace	Currently Farmed.	Weakly developed
GR 931 - F. Burciaga Homesite (2011.02x18)	Prehistoric	362-375	Feature 83	Buried	Cleared Area from nearby house	Holocene Terrace	Before 1914 (Southworth 1919)	Weakly developed
GR 485 - Lucero A-5 Field (2011.12x9)	Historic	376-399	Feature 30 (Spec #s 120-121, 128 - 145)	Buried	Fallow since unknown time. Agricultu	Holocene Terrace	Fields in 1914. (Southworth 1919)	Weakly developed

			Feature 31 (Spec #s 122-123, 148-165)		ral use evident on surface. Probably before mechanical clearing.			
GR 485 - Lucero A-6 Field (2011.12x 10)	Historic	400-411	Feature 32	Buried	Fallow since unknown time. Agricultural use evident on surface. Probably before mechanical clearing.	Holocene Terrace	Fields in 1914. (Southworth 1919)	Weakly developed
GR 782 - E. Marietta Homesite (2010.01x 12)	Historic	1-5	Feature 19	Buried	Cleared Area from nearby house, surrounded by agricultur	Holocene Terrace	Within 2 decades	Well-developed

					al land			
GR 522 - P. Mendivil Homesite (2011.02x23)	Prehistoric	412-424	Feature 1381	Buried	Cleared Area from nearby house, surrounded by agricultural land	Holocene Terrace	Before 1914 (Southworth 1919)	Weakly developed
GR 485 - L. White Homesite (2011.02x25)	Historic	425 - 436	Feature 33	Buried	Cleared Area from nearby house, surrounded by agricultural land	Holocene Terrace	1952 USGS map has a canal directly SW of excavation.	Weakly developed

GR 782 - Homesite	Prehistoric	476 - 489	Feature 21	Buried	Cleared Area from nearby house	Holocene Terrace	Before 1914 (Southworth 1919)	Well-developed

Because soils are dynamic palimpsests that result from the effects of time, topography, climate, parent material, organisms, and human use (Jenny 1941; Jenny 1994; Sandor 1995; Sandor and Homburg 2010), multiple factors need to be considered before directly comparing soils from two or more fields. Because this dissertation focuses on a landscape scale, climate and soil organisms are assumed constant throughout the sampled area. Pilot research performed by the GRIC, however, indicates that landscape geomorphology and past and current land uses affect soil characteristics (Waters and Ravesloot 2000). For this study, it was essential to control these factors when comparing data from the prehistoric and historic fields in order to isolate the driving factors of interest – longevity and intensity of prehistoric and historic agricultural use. Thus, a matrix of these variables was created (see Tables 5.2 and 5.4 for explanation of field variables and Table 5.3 for sampled sites and their associated variables) to track the variables that may affect soil characteristics in each of the sampled locations. These variables included geomorphology, period of last agricultural use, the presence of a modern field above the sampled field, the depth of the prehistoric or historic agricultural field, and degree of B horizon development (well-developed indicates the presence of a argillic horizon, while weakly developed indicates a cambic horizon) (Table 5.4).

The topography and parent material (representing the geomorphology of the study area) must be considered to identify samples that can be directly compared (Homburg et al. 2005; Sandor et al. 2007; Sandor and Homburg 2010). Fortunately, the GRIC has been subject to intensive geoarchaeological sampling in the past, resulting in numerous reports and publications on the geomorphological contexts of the GRIC (Ravesloot and Waters

2004; Waters and Ravesloot 2001; Waters 2008; Wright et al. 2011; Figure 5.4). These publications and reports were used to inform the selection of sampling sites for appropriate comparability, and their interpretations of the geomorphology were confirmed during fieldwork (Tables 5.3 and 5.4).

Table 5.4: Matrix of Characteristics Important to the Paleoecological Indicators on the GRIC

Characteristic Affecting Soils	**How it Will Affect Soils**	**Method of Determining Presence and Impact on Soil Interpretation**
Degree of Soil Development	Degree of the soil development affects clay movement through the profile; some nutrients and/or salts and sodium will have leached out over time.	Characterization of the Soil Profile. Lab work on nutrient levels and soil texture in the vertical column of profile sampling.
Geomorphic Age and Setting	Parent material and time of soil development will differ depending on the geomorphic surface of the soil.	Assessed based on maps from Ravesloot and Waters 2002; Waters and Ravesloot 2001; Waters 2008. Confirmed by Strawhacker during fieldwork.
Buried or Surface Field	Different erosional and disturbance forces affect fields.	Field observation while collecting samples.
Period of Last Agricultural Use	Can affect how the soil has changed after variable years of fallow.	GIS database of historic maps and aerial photographs.
Under a Modern Field	Modern application of fertilizers can leach nutrients into buried horizons. Plow zones can disturb buried prehistoric and historic fields.	Samples were collected in a vertical column down the trench profile to understand how nutrients may have leached during fertilizer application.

Some of the modern GRIC landscape is currently farmed, and many of these modern fields are located above prehistoric and historic fields and features. The cultivation of these modern fields can impact the prehistoric and historic strata of interest.

For example, nutrients contained in fertilizers applied to the fields can leach down to the strata beneath the surface, thus affecting some indicators of soil fertility in prehistoric or historic fields. Accumulated salts and sodium could also be leached from buried agricultural fields with the addition of more irrigation water moving down the soil profile. Considering the impact of the modern fields on buried prehistoric and historic fields is essential when interpreting the results of the soil analyses. Because these fields may have elevated nitrogen and phosphorus levels from applied fertilizers, these soil characteristics from samples from fields under modern fields should not be compared to those from fields that are not so located until it has been determined that they have not been contaminated (see Chapter 6).

Furthermore, although the agricultural economy changed throughout the historic period, dating of the historic agricultural fields is not precise enough to test the ecological implications of specific changes during the historic period. Dating is precise enough, however, to compare prehistoric and historic field contexts. Early historic agriculture is argued to have taken place in the central part of the reservation on the south side of the river between Pima Butte and the Blackwater area (Doelle 1981; Ezell 1961; Southworth 1919; Woodson 2003; see Figure 3.7 for high concentration of early historic villages on south side of the river), and thus this area was a particular focus of historic field sampling as it is the most likely area for evaluating the impact of the Spanish market for wheat. In order to obtain large enough sample sizes for the historic period, however, historic fields through the early 1900s were sampled, since these later historic fields dominate the GRIC landscape.

Abandoned modern (AD 1950 – present) fields were also identified so that they were not sampled as "historic." To determine when a field was last cultivated, an extensive GIS database was created with historic maps of agricultural fields from 1914 (Southworth 1919) and aerial photographs taken approximately every 20 years from 1936 to present. This database displays the parts of the study area that have been farmed over the past 100 years. Those fields farmed before AD 1950 are considered historic fields, while those farmed after AD 1950 are considered modern. AD 1950 is used to separate the periods because the modern industrial plow was introduced to the area shortly after this date, altering the nature of agriculture on the GRIC (Wilson 1999).

Addressing the Research Themes with Soil Analyses

To address the two research goals – the effects of the longevity of irrigation and of the intensification of agriculture on the enhancement or degradation of soils - soil samples from irrigated agricultural fields on the north coast of Peru and the middle Gila River were tested for characteristics important to agricultural crop productivity, including total and available nitrogen, available phosphorus, organic and inorganic carbon, electrical conductivity, sodium adsorption ratio, bulk density, and pH (Table 5.5). Table 5.5 outlines ideal levels of these soil characteristics for crop cultivation and then provides expectations of degradation or enhancement for each soil analysis.

Table 5.5: Soil Analyses and Their Significance for Agricultural Production

Soil Property Tested for Degradation	**Ideal Levels for Cultivation**	**Criteria for Recognizing Enhancement**	**Criteria for Recognizing Degradation**	**Significance for Agricultural Production**
Highly Important for Cultivation				
Available Phosphorus (mg P per kg soil)	Values between 4 and 7 mg P/kg soil are considered low for irrigated production	Elevated available phosphorus in fields compared to landscape controls.	Lower available phosphorus in fields compared to landscape controls.	Phosphorus is an essential ecological indicator of healthy soil and a key macronutrient for agricultural crop productivity, second only to nitrogen.
Total Nitrogen (g N per kg soil)	Values under 1 g N per kg of soil are considered very low for agricultural production.	Levels of total nitrogen under 1 g N per kg of soil (both the Pampa and GRIC are below this level) would require additions of nitrogen to soils.	Lower total nitrogen in fields compared to landscape controls.	Nitrogen is an essential nutrient to plant growth, and its decline frequently accompanies declining organic matter.
Soil Texture, proportion of % Clay, % Silt, and % Sand	Equal proportions of all particle sizes (loamy soils) are ideal for agriculture	The addition of finer sediments (clays and silts) to coarse, sandy soils. Higher proportions of clays and silts.	A high proportion of any particle size may result in soil degradation.	Finer sediments in arid soils can store water for longer periods of time and frequently have higher nutrient levels.
Organic Carbon (g C per kg soil)	Ideal levels are 20 g of organic carbon per kg of soil,	Elevated organic carbon levels in fields, compared to landscape	Less organic carbon in fields compared to landscape	Organic C is an essential nutrient for plant growth, and its decline is

	although arid soils will likely be much lower than this.	controls.	controls.	associated with plow agriculture.
Sodium Adsorption Ratio	Levels above 2 indicate sodicity problems for very sensitive crops.	Lower SAR in fields compared to landscape controls.	Elevated SAR in fields compared to landscape controls.	SAR indicates an accumulation of exchangeable sodium, indicating alkalization of soils.
Electrical Conductivity (dS/m)	Below 4 dS/m	Maintenance or improvement of saline conditions below 4 dS/m, compared to landscape controls	Above 4 dS/m means soils are considered saline; Effects on crop productivity are dependent on the crop and depth of the rooting zone.	EC is a measure of soil salinity and indicates how well a liquid solution can carry an electrical current, which is affected by salt content.
Less Important for Cultivation, but Analyzed to Understand Soil Profile and Development				
Available Nitrogen (Nitrate and Ammonium) (mg N per kg soil)	Ammonium: 2-10 mg N/kg soil is typical Nitrate: Less than 30 mg N/kg soil would see improved plant cultivation with added fertilizer	Higher levels of available nitrogen in fields compared to control samples.	Lower levels of available nitrogen in fields compared to control samples.	Numbers are highly dependent on daily moisture and temperature patterns, as well as soil depth. While they can provide insight into what is available to plants, it can be hard to control other factors to understand variability across a landscape.

Bulk Density (g/cm^3)	Ideal for cultivation: ~ 1.33 g/cm^3	Maintenance or improvement of bulk density levels compared to landscape controls, if outside ideal range.	Bulk densities below 0.90 g/cm^3 and above 1.60 g/cm^3 can begin to inhibit plant cultivation.	Any increase in bulk density indicates compaction of soils, which can make it difficult for roots and water to penetrate soil.
Inorganic Carbon (g C per kg soil)	Helpful only for understanding amount of calcium carbonate in the soil, which can control pH and SAR.	N/A	N/A	Not essential for plant growth, but provides insight into alkalinity (measured by pH and SAR) of soil.
Total Carbon (g C per kg soil)	Helpful only for understanding the ratio of inorganic to organic carbon in soil. Not useful for interpreting effects on plant cultivation.	N/A	N/A	Total carbon is elevated in arid soils due to amount of inorganic carbon (calcium carbonate) in soils. Organic carbon is a better indicator for plant cultivation
pH	Between 6.0 and 7.0	Normal levels around 8.0 are expected for both GRIC and the Pampa. Plants are likely adapted to that range.	Numbers approaching a pH of 8.5 would inhibit nutrient availability.	Higher pH levels can indicate sodic conditions, which limit nutrient availability to plants.

Inferring Longevity of Irrigation Agriculture and Measuring its Effect on Soil Quality on the Middle Gila River. The prehistoric fields along middle Gila River have been farmed for over a millennium and historic fields have been farmed for over two hundred years. Fields from both time periods can indicate whether long-term irrigation resulted in degradation or enhancement to natural soil quality. To measure how the longevity of irrigation agriculture affected soils along the middle Gila River, soils from all fields, prehistoric and historic, are compared to control samples, which reflect the unfarmed landscape. Individual fields are assumed to have been farmed for extended periods of time due to the investment involved in creating the fields and the irrigation infrastructure. The amount of time and labor devoted to the construction of canals likely indicates that associated fields would have been used for a long period of time.

Inferring Longevity of Irrigation Agriculture and Measuring its Effect on Soil Quality on the North Coast of Peru. Farmers along the Rio Sanjón used a variety of strategies in order to maintain soil quality under intensive irrigation for over 600 years, and the prehispanic agricultural fields reflect this diversity in their structure and organization. Previous research showed that soils were prohibitively low in nitrogen and would have required additions to the soil to maintain crop production for hundreds of years (Nordt et al. 2004). Similarly, salinity levels are also low in the soils, supporting long-term crop production. Soils are analyzed at a number of different scales to understand how farmers on the Pampa may have maintained and improved soil quality in their fields. The next chapter presents the suite of strategies, including adding fine silts and organic matter to soils through irrigation water and using ridges to draw salts away from planting surfaces through capillary action, by presenting a number of soil analyses comparing ridges and furrows and unique fields that provide insight into these diverse strategies.

Inferring Intensification and Measuring its Effect on Soil Quality on the Middle Gila River: On the middle Gila River, agriculture intensified from the primarily subsistence-based prehistoric period to the cash-based historic period. As argued in Chapter 3, O'odham farmers intensified agriculture from prehistoric levels of production to meet the demands of new markets introduced by Spanish missionaries and American explorers. In order to measure the effects of the intensification of agriculture on soil quality on the middle Gila River, soils from the more intensively farmed historic fields are compared to soils from prehistoric fields to measure whether the intensification of agriculture resulted in enhancement or degradation of soils.

Inferring Intensification and Measuring its Effect on Soil Quality on the North Coast of Peru: On the Pampa de Chaparrí, the intensification of agriculture is inferred within walled fields compared to fields that are not located within a wall. In Chapter 4, I argued that walled fields are rare across the north coast of Peru and are associated with large, bureaucratic architecture in the Chimú capital of Chan Chan. To measure how the intensification of agriculture affected soils on the Pampa, the soils from two walled fields are compared to soils from fields that were not enclosed by a wall to understand how the intensification of agriculture within the walled field affected soil quality.

Soil Analysis

Soil Laboratory Methods Description

After soils were collected from field contexts, I performed initial processing of the samples and a selection of the analyses in the Terrestrial Ecosystem Ecology Research Laboratory, managed by Dr. Sharon Hall, and at Goldwater Environmental Laboratory, both at Arizona State University. Tests to evaluate soil fertility mirror those run during previous research on dry farmed soils in the U.S. Southwest and those run from the pilot studies performed on the north coast of Peru and on the middle Gila River (Sandor 2010). Additionally, other properties that are appropriate for understanding irrigated agricultural soils were evaluated, such as electrical conductivity and sodium absorption ratio (Hall, personal communication; Homburg et al. 2005; Sandor 2010; Sandor and Homburg 2010). The soils were analyzed for bulk density, pH, texture, total nitrogen, available nitrogen (ammonium and nitrate), organic carbon, calcium carbonate (inorganic carbon), available phosphorus, calcium, magnesium, electrical conductivity, sodium, and potassium (see Table 5.5 for indicators of degradation and enhancement of soils).

After field collection, soils were air-dried for 3-4 days and then packed and boxed for transport back to Arizona State. When soils arrived at Arizona State, they were sieved to 2 mm fraction for analysis. During sieving, aggregates of soil were gently broken up for sieving. Large pieces of organic matter, like roots, and any particles greater than 2 mm (gravels) were weighed to determine percentage of sample that is gravels and then discarded. Sieved soils were analyzed for a suite of physical and biogeochemical properties using Central Arizona–Phoenix, Long Term Ecological Research (CAP LTER) standard protocols (http://caplter.asu.edu/) and according to previous research done on ancient agricultural fields (Sandor 2010).

Soil particle size (texture) was determined using the hydrometer method (100 mL of 50 g/L sodium hexametaphosphate and 40 g of soil), with a hydrometer measurement taken at 7 hours after initial mixing of the sediment to determine the clay fraction, followed by sieving to 53 µm for sand content and calculating silt content by difference. Gravimetric air dry soil moisture (g/g dry soil) was determined by drying 30 g of soil for 24 hours at 105°C and calculated as: Wg= Wms-Wds/ Wds; where Wms is the mass of the fresh (moist) soil and Wds is the mass of the soil dried at 105° C for 24 hours.

Soil organic matter (SOM) (%) was estimated by the loss-on-ignition method as ash-free dry mass following combustion of oven-dried soils for 6 hours at 550°C. Inorganic carbon, or calcium carbonate, was also measured through the loss-on-ignition method. Similar to the calculation of soil organic matter, 30 g of oven-dry soil was weighed following combustion of the sample for 3 hours at 900°C and the difference was calculated, which should have resulted in a reliable number for inorganic carbon. After comparing the numbers of both soil organic matter (organic carbon) and inorganic carbon to levels of total carbon, it became clear that levels of organic and inorganic carbon were artificially elevated. This artificial elevation in inorganic and organic carbon numbers is most likely due to the low burning point of certain salts in the soil thus artificially elevating the amount of both organic and inorganic carbon in the soil (Sandor, personal communication). Because of problems with calculating organic and inorganic carbon by the loss-on-ignition method, all of the samples from the Gila River Indian Community were sent for analysis to Dan Hirmas at the Pedology Lab at the University of Kansas. Hirmas performed coulometric titration analysis on the soil (see Hirmas et al. 2012 for details). Funds were not available for this analysis on the soil samples from the Pampa de Chaparrí, so organic carbon levels are simply reported as “organic matter loss on ignition” to indicate that this number may be artificially elevated.

Ammonium (μg NH_4^+ per 1 g dry soil) and nitrate + nitrite (summed as μg NO_3^- per 1 g dry soil) concentrations were measured using 10 g of soil extracted in 50 mL of 2M KCl by shaking for 1 hour and filtering through pre-leached Whatman #42 ashless filters. The extracts were frozen until colorimetric analysis using a Lachat Quickchem 8000 autoanalyzer. Phosphate (μg PO_4^{3-} P per 1 g dry soil) concentration was measured using 2 g of soil extracted in 40 mL of 0.5M $NaHCO_3$ by shaking for 1 hour and filtering through pre-leached Whatman #42 ashless filters. The extracts were frozen until colorimetric analysis using a Bran-Luebbe Traacs 800 Autoanalyzer.

A portion of the sieved soils (approximately 5 g) was milled until ground (typically for 4 minutes) for submission to the Ecosystems Analysis Lab at the University of Nebraska-Lincoln for total carbon and nitrogen analysis. The milled samples were measured on the COSTECH Analytical Elemental Combustion System 4010 (ESC 4010) Instrument. Their measurement of total carbon was, on average, within 5% of what was measured by the analysis done by Dan Hirmas.

120 g of air-dried and sieved soils were submitted to the Soil, Plant, and Water Analysis Laboratory at Stephen F. Austin State University for saturated paste analysis. The saturated paste analysis was done following the general procedure of USDA

Handbook 60 (2010). The soil was mixed with deionized water to create a saturated paste. After a set equilibration time, vacuum funnels were used to extract water from the saturated soil, to isolate the saturation extract from the paste. The saturation extract was then run on the Inductively Coupled Plasma (ICP) to determine concentrations of the elements. From this analysis, pH, electrical conductivity, and concentrations of sodium, calcium and magnesium were measured to determine Sodium Adsorption Ratio (SAR), all of which provide insight into salinity and sodium levels of soils.

All of these analyses were then converted to appropriate units for measurement and comparison and compiled into a spreadsheet for analysis. Statistical analysis of the soils data was performed in Statistical Package for the Social Sciences (SPSS for IBM) and figures were created in both SPSS and SigmaPlot. A variety of statistical analyses were used to compare datasets and soils at varying spatial levels (including between and among fields, within fields, etc.), including ANOVA, paired t-tests, correlations, regressions, and general descriptive statistics. The salient results of these analyses are presented in the following chapters.

Chapter 6

EVALUATING THE RELATIONSHIP BETWEEN LONG-TERM IRRIGATION AND SOIL QUALITY

This chapter presents data directly from agricultural soils to document how soil quality across the middle Gila River Valley and the north coast of Peru was affected by the longevity and intensification of irrigation agriculture. Soils comprise the basis of agricultural production and can be significantly affected by changes in the agricultural system. In Chapter 2, I argued that in arid environments, soil quality is highly vulnerable to degradation under intensive agricultural conditions, unless agricultural strategies are incorporated to replace nutrients removed through plant harvest. The following sections present results from arguably the most intensive agricultural system found in arid environments – irrigation systems – from two different regions of the world. I argue that farmers in both regions successfully created strategies to manage the quality of their soils over the long-term. These two case studies diverge, however, in terms of the impacts of intensification of irrigation agriculture on soil quality. On the middle Gila River, the intensification of agriculture resulted in the enhancement of organic carbon and total nitrogen in soils, while more intensively used walled fields on the Pampa de Chaparrí showed signs of degradation compared to those fields managed less intensively.

Soil Results from the Middle Gila River

Overall, the soil results show that, not surprisingly, soils are highly varied across the GRIC landscape. The palimpsest of alternate downcutting and aggrading of the river, in addition to over a millennium of intensive human use, has resulted in a diverse landscape. Table 6.1 shows the general characteristics of all collected soils from agricultural field strata from the middle Gila River. These numbers indicate that the fields are, on average, slightly saline and sodic, although not to the point that would seriously limit crop productivity. Texturally, these fields are low in coarse fragments and high in silt. The average pH of the fields is moderately alkaline (~ 8.1), like many other arid soils, which does not greatly limit agriculture, but is above optimal soil pH range for crop productivity (Brady and Weil 2008). Available phosphorus and total nitrogen levels are very low, and agricultural production in the past would likely have been higher if nitrogen and phosphorus were added to the soil, based on greenhouse experiments done on prehistoric dryland fields (Sandor and Gersper 1988). Available phosphorus and total nitrogen values are lower, however in control samples, indicating that these low values are not due to degradation (Table 6.2).

Table 6.1: General Soil Characteristics (mean, (standard deviation)) from Sampled Field Strata By Depth across the GRIC. Total N= 215

		Depth from Surface					
Soil Characteristic	**Ideal Level for Plant Cultivation**	**0-15 cm (n = 23)**	**16-30 cm (n=14)**	**31-45 cm (n=67)**	**46-60 cm (n = 66)**	**61-75 cm (n=20)**	**76-90 cm (n=25)**
Characteristics Essential for Successful Plant Cultivation							
% Clay	33%	9.0 (2.5)	16.0 (6.0)	18.9 (9.0)	21.8 (15.0)	29.7 (6.7)	17.0 (10.0)
% Silt	33%	63.0 (7.5)	68.2 (14.5)	40.9 (13.1)	45.1 (22.9)	49.0 (9.3)	41.8 (12.9)
% Sand	33%	28.0 (9.7)	15.8 (0.7)	40.1 (20.5)	33.1 (29.6)	21.3 (13.6)	41.2 (20.0)
% Coarse Fragments	Dependent on soil.	N/A	0.5 (0.7)	3.9 (7.6)	2.2 (3.0)	0.7 (0.5)	1.8 (1.8)
Organic Carbon (g C/kg soil)	20	8.4 (2.2)	9.2 (2.6)	4.7 (2.6)	4.2 (2.5)	3.4 (1.2)	2.9 (1.5)
Total Nitrogen (g N/kg soil)	Greater than 5	0.72 (0.18)	0.97 (0.36)	0.48 (0.19)	0.41 (0.22)	0.37 (0.10)	0.36 (0.21)
Electrical Conductivity (dS/m)	Less than 4	0.7 (0.2)	4.0 (2.2)	11.4 (18.2)	9.2 (9.1)	5.5 (5.6)	4.2 (4.7)
Sodium Adsorption Ratio	Less than 2	0.8 (0.5)	3.1 (2.2)	10.5 (8.3)	11.4 (6.8)	9.1 (2.0)	5.6 (2.9)
Available	Greater than	N/A	5.8 (2.3)	3.7 (2.1)	3.0 (1.6)	2.2 (0.9)	3.17 (3.3)

Phosphorus (mg P /kg soil)	10						
Characteristics Less Important for Successful Plant Cultivation							
Bulk Density	1.33	1.34 (0.15)	1.13 (0.08)	1.18 (0.10)	1.22 (0.18)	1.02 (0.11)	1.12 (0.12)
pH	6.0 - 7.0	8.5 (0.15)	8.0 (0.2)	8.1 (0.5)	8.0 (0.34)	8.1 (0.3)	8.0 (0.4)
Inorganic Carbon (g C/kg soil)	N/A	5.6 (1.3)	6.9 (0.9)	7.2 (2.1)	5.8 (2.1)	6.4 (2.3)	5.5 (1.5)
Total Carbon (g C/kg soil)	N/A	14.0 (1.8)	16.0 (2.1)	11.9 (3.6)	9.9 (3.7)	9.8 (1.8)	8.4 (2.6)
Nitrate (mg N/kg soil)	Greater than 30	7.00 (2.88)	156.51 (157.7)	74.33 (109.73)	57.74 (68.22)	17.82 (34.53)	60.16 (1111.63)
Ammonium (mg N/kg soil)	2-10	2.91 (1.00)	2.92 (2.95)	2.82 (2.76)	2.46 (3.85)	1.50 (1.20)	2.15 (2.42)
% Soil Moisture	N/A	2.40 (0.22)	4.46 (0.95)	3.50 (1.73)	3.88 (2.06)	4.72 (1.30)	3.34 (1.73)

As described in Chapter 5, many driving factors can influence the characteristics of the soil profile. It was important for this project to isolate the anthropogenic impacts (as opposed to other natural forces, such as alluvial downcutting) on the soils to be able to interpret the various effects of intensification of agriculture and long-term irrigation. In order to isolate the anthropogenic impact of irrigation agriculture, these other factors, including geomorphology and the presence of a modern agricultural field, were evaluated. Appendix C presents the results of this evaluation, and this analysis indicates that the only factor that is driving soil development, in addition to irrigation agriculture, is the geomorphic surface that the prehistoric or historic fields was located on. All soil profiles and field observations are provided in full detail in Appendix A.

Assessing Research Themes 1 and 2 on the Middle Gila River – The Relationship between the Longevity and Intensification of Irrigation Agriculture and Soil Quality

In order to assess the two research themes, soils from prehistoric and historic fields are compared to landscape control samples to ascertain whether long-term irrigation resulted in degradation or enhancement in soil quality (Tables 5.5 and 6.1 for indicators in soil characteristics). To assess how the intensification of agriculture affected soil quality, historic soils, more intensively cultivated than prehistoric fields with the transition to the market economy, are compared to prehistoric soils. Thus, both prehistoric and historic fields inform the effects of *longevity* of irrigation on soils, while the more intensively farmed historic fields indicate the effects of the *intensity* of irrigation on soils when compared to the less intensively used prehistoric fields. This analysis addresses whether in either case irrigation agriculture degraded or enhanced agricultural soils.

The following sections first present data on soil characteristics from prehistoric and historic fields, with an evaluation of which characteristics are degraded or enhanced in prehistoric and historically farmed fields, compared to landscape controls. Second, the two research themes are evaluated with these results. The results, while mixed depending on geomorphic context, also indicate that long-term irrigation added fine sediments and nutrients to the soils, with little evidence for widespread salinization, and that intensively farmed historic fields show evidence for enhancement.

Comparing Prehistoric Fields, Historic Fields, and Landscape Controls- Physical and Chemical Properties

Figures 6.1 a-n display the box plots of each tested soil variable, and Table 6.1 provides the descriptives and ANOVA results indicating where there are statistically significant differences among prehistoric fields, historic fields, and control samples. Table 6.2 provides a list of all soil characteristics and their statistical significance among all sampled contexts. The box plots show the distribution of the data for each soil characteristic. The box plot borders display the lower and upper quartiles of the data, with the dividing line indicating the median. The whiskers display the minimum and maximum of the dataset for each soil characteristic, excluding outliers. The stars plotted outside of the box show the outliers within the data (calculated as 3/2 times outside the upper or lower quartile)

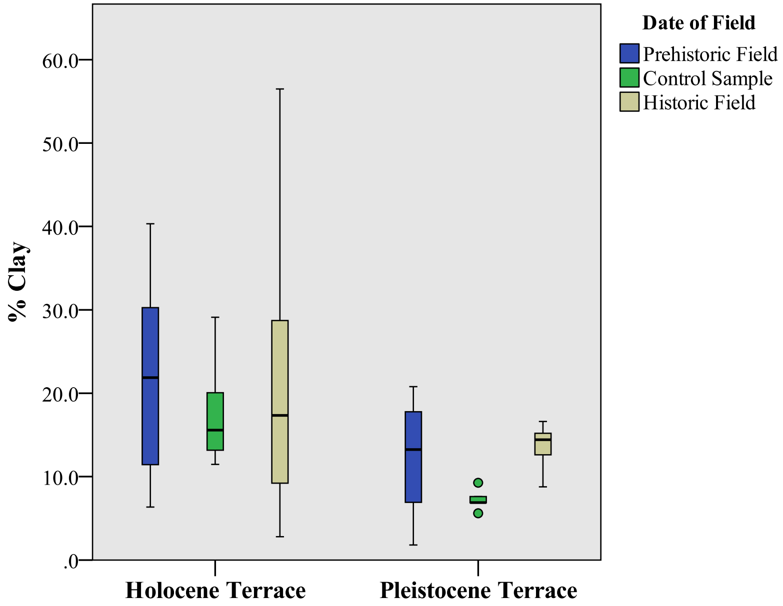


Figure 6.1a: Percent Clay. Percent clay is significantly lower in the control Samples on the Pleistocene Terrace.

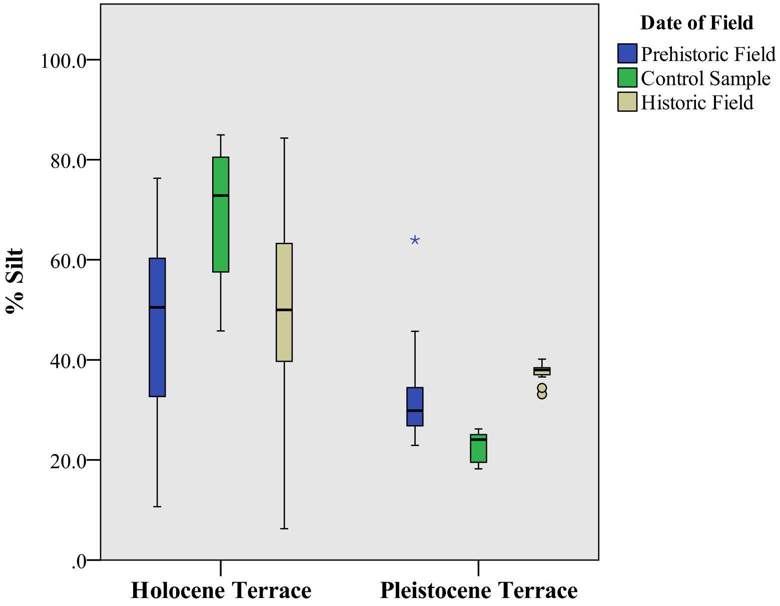


Figure 6.1b: Percent Silt. Percent silt is significantly higher in the control samples on Holocene Terrace and significantly lower in control samples on Pleistocene Terrace.

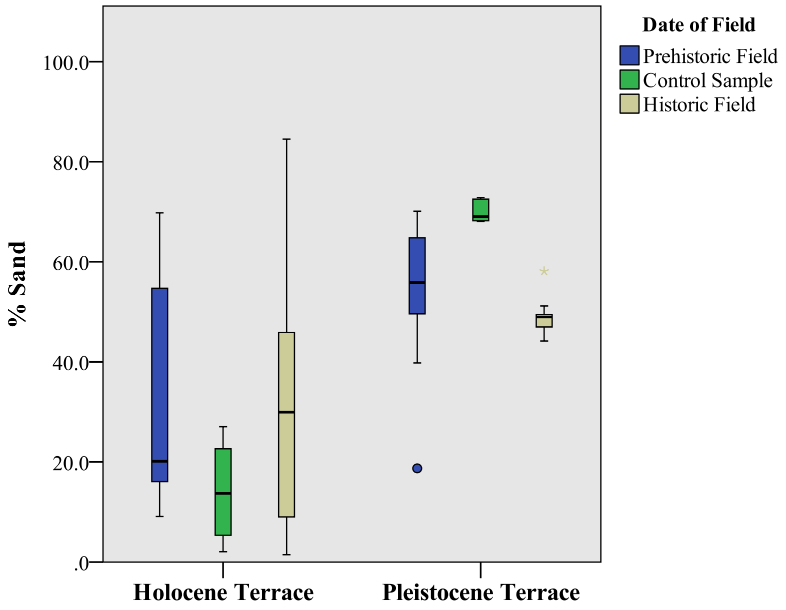


Figure 6.1c: Percent Sand. Percent sand is significantly lower in control samples on the Holocene Terrace and significantly higher in control samples on the Pleistocene Terrace.

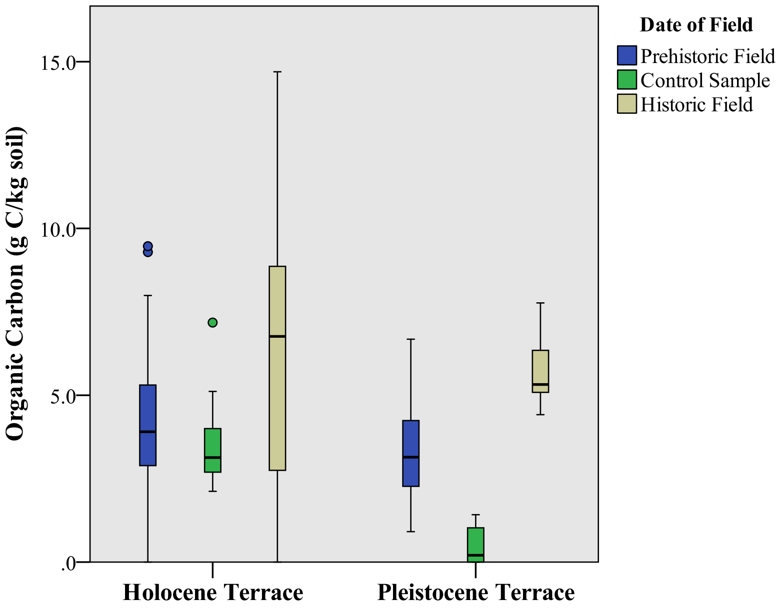


Figure 6.1d: Organic Carbon. Organic Carbon is significantly higher in all fields compared to control samples. Historic fields are significantly higher than prehistoric fields.

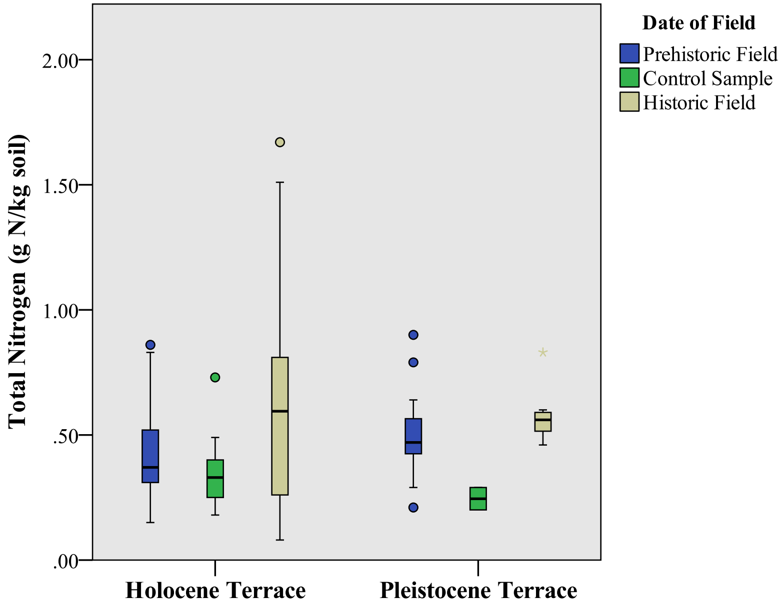


Figure 6.1e: Total Nitrogen. Total Nitrogen is significantly higher in all fields compared to control samples. Historic fields are significantly higher than prehistoric fields.

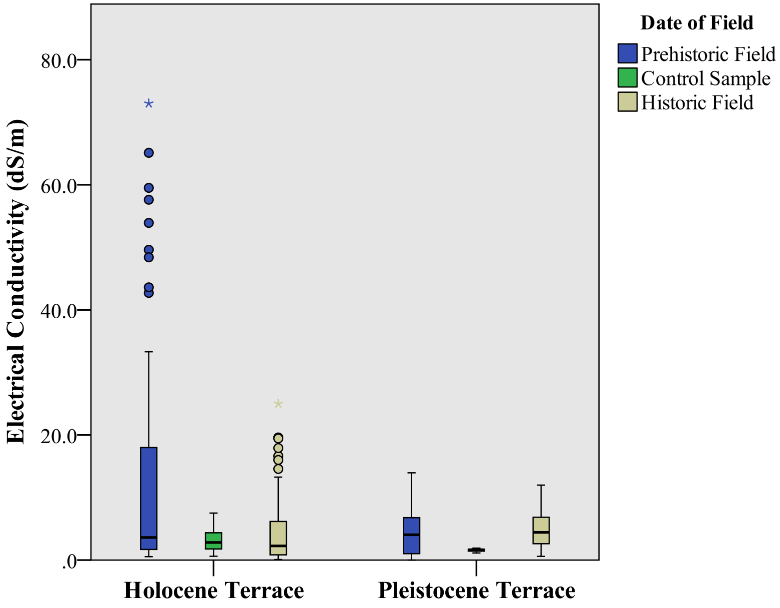


Figure 6.1f: Electrical Conductivity. Electrical conductivity is significantly higher in the prehistoric fields on the Holocene Terrace.

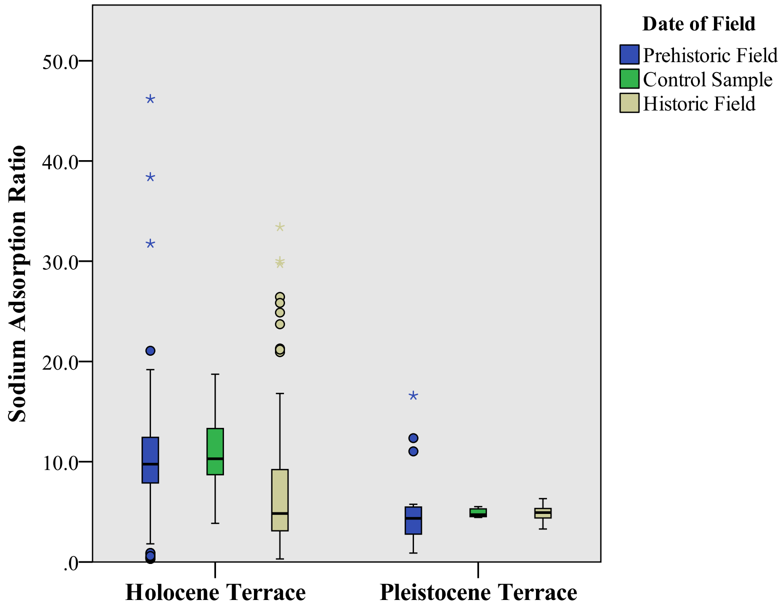


Figure 6.1g: Sodium Adsorption Ratio. SAR is significantly lower in historic fields on the Holocene Terrace.

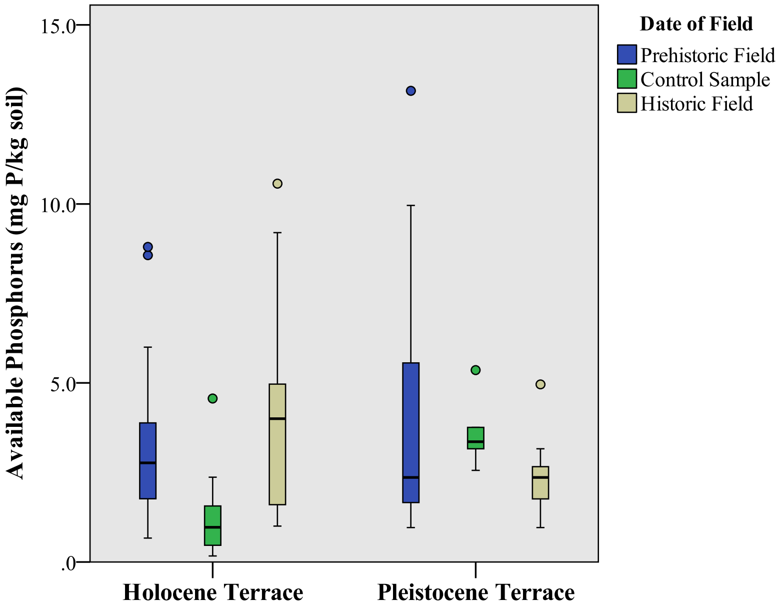


Figure 6.1h: Available Phosphorus. Available phosphorus is significantly lower in control samples compared to all fields on the Holocene Terrace.

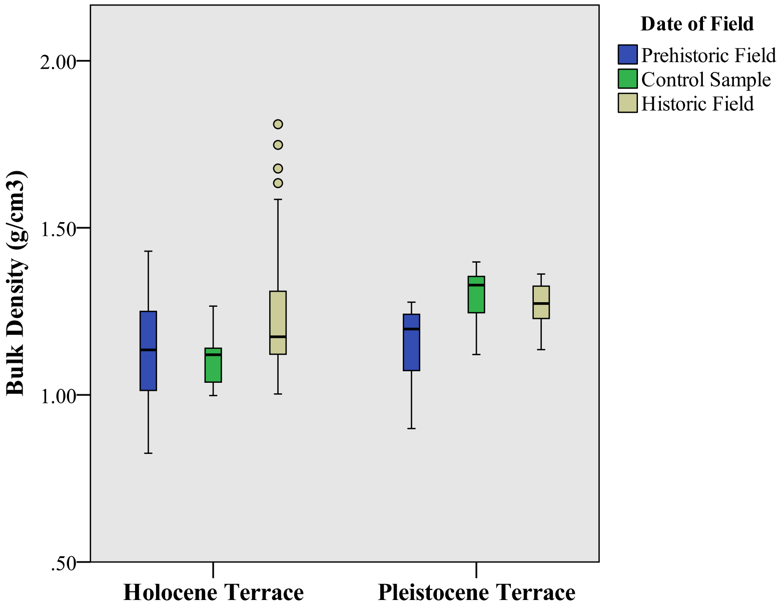


Figure 6.1i: Bulk Density. Bulk density is significantly higher in historic fields on the Holocene Terrace.

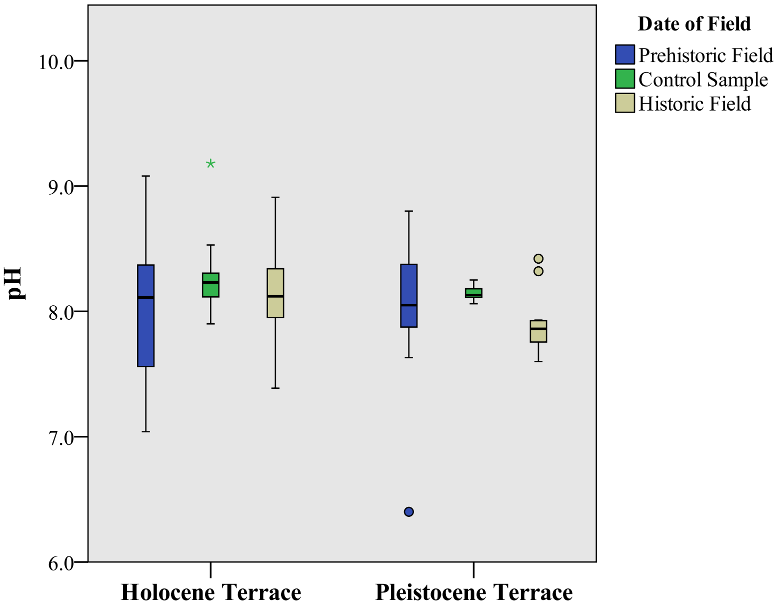


Figure 6.1j: pH. pH is significantly higher in control samples on the Holocene Terrace.

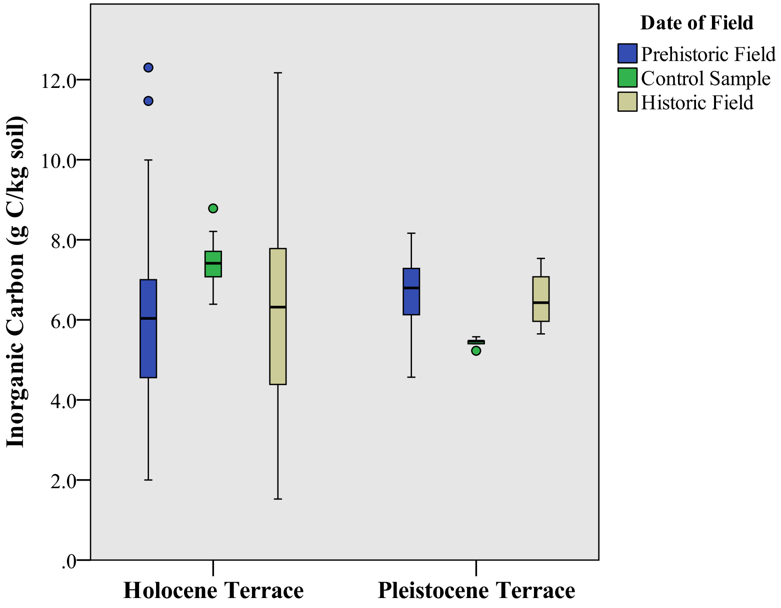


Figure 6.1k: Inorganic Carbon. Inorganic carbon is significantly higher in control samples compared to all fields. Inorganic carbon is also significantly higher in historic fields than in prehistoric fields on the Holocene Terrace. On the Pleistocene Terrace, inorganic carbon is significantly lower in the control samples compared to all fields.

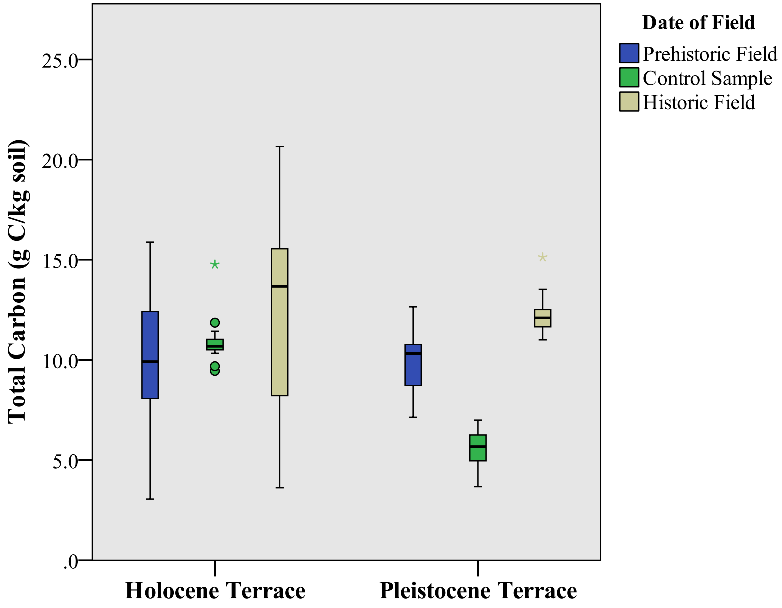


Figure 6.1l: Total Carbon. On the Holocene Terrace, total carbon is significantly higher in the historic fields and lower on the prehistoric fields. On the Pleistocene Terrace, all fields are significantly higher than control samples and the historic fields are significantly higher than the prehistoric fields**.**

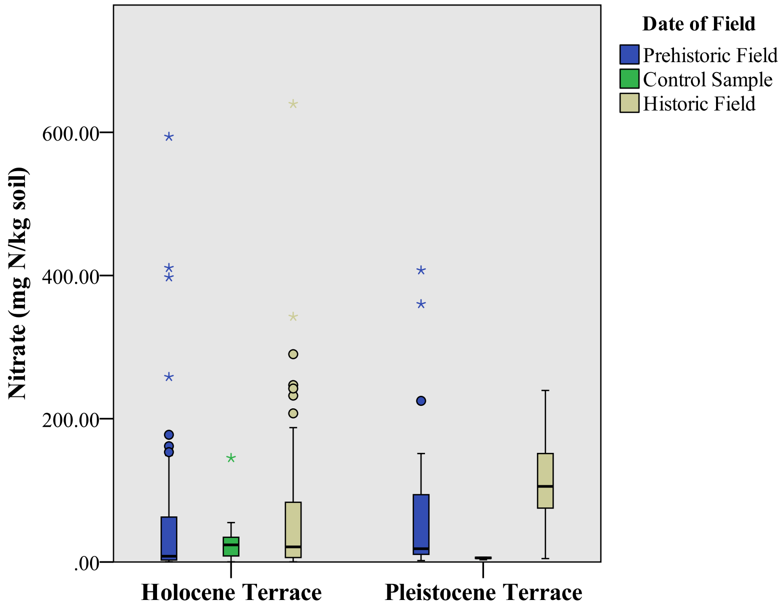


Figure 6.1m: Nitrate (Available Nitrogen). No significant differences.

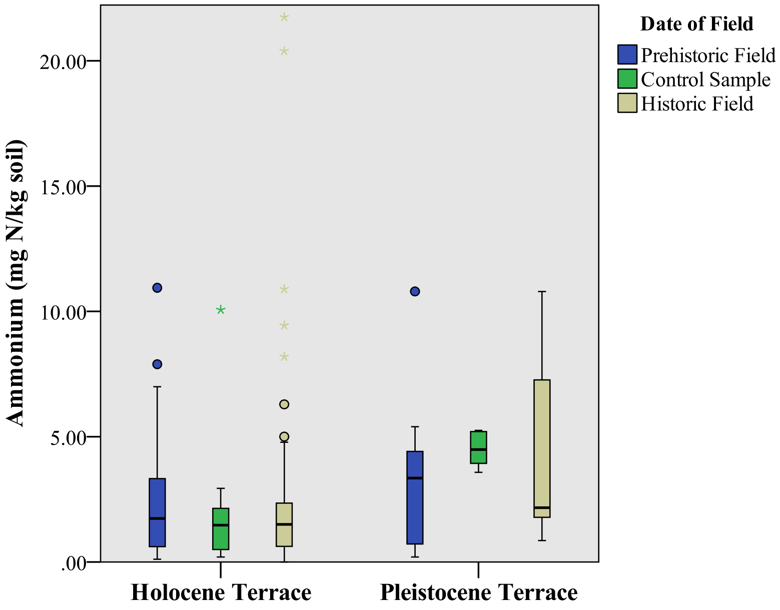


Figure 6.1n: Ammonium (Available Nitrogen). No significant differences.

Table 6.2: Comparison of Soil Chemical Properties for Field Horizons among Prehistoric, Historic and Control Samples

Geomorphic Surface		% Clay	% Silt	% Sand	Organic Carbon (g C/kg soil)
Holocene Terrace	Prehistoric Field	21.4 (10.2)	48.3 (16.8)	30.3 (20.7)	4.2 (1.9)***
	Control Sample	17.6 (5.6)	68.4 (13.3) ***	14.0 (9.4)**	3.5 (1.3)***
	Historic Field	20.7 (14.5)	48.7 (18.6)	30.6 (24.7)	6.3 (3.7)***
Pleistocene Terrace	Prehistoric Field	12.6 (5.6)	32.2 (9.1)	55.2 (12.1)	3.4 (1.5)***
	Control Sample	7.3 (1.3)**	22.6 (3.5)**	70.1 (2.4)***	0.5 (0.7)***
	Historic Field	13.8 (2.2)	37.4 (2.0)	48.9 (3.8)	5.8 (1.1)***

Note. Data are means (standard deviations in parentheses) for 18 sampling sites.
One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate different from other field contexts within the same geomorphic surface)

Geomorphic Surface		Total Nitrogen (g N/kg soil)	Electrical Conductivity (dS/m)	Sodium Adsorption Ratio	Available Phosphorus (mg P/kg soil)
Holocene Terrace	Prehistoric Field	0.43 (0.18)***	12.9 (17.4)***	10.6 (7.5)	3.0 (1.6)
	Control Sample	0.34 (0.14)***	3.2 (1.9)	10.8 (3.9)	1.2 (1.2)***
	Historic Field	0.58 (0.35)***	4.8 (5.7)	7.7 (7.7)**	4.0 (2.3)
Pleistocene Terrace	Prehistoric Field	0.49 (0.16)	4.7 (3.9)	5.2 (3.9)	4.0 (3.4)
	Control Sample	0.25 (0.06)**	1.6 (0.3)	4.9 (0.5)	3.6 (1.1)
	Historic Field	0.57 (0.10)	5.0 (3.3)	4.8 (0.9)	2.4 (1.1)

Note. Data are means (standard deviations in parentheses) for 18 sampling sites.
One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate different from other field contexts within the same geomorphic surface)

Geomorphic Surface		Bulk Density	pH	Inorganic Carbon (g C/kg soil)	Total Carbon (g C/kg soil)
Holocene Terrace	Prehistoric Field	1.13 (0.15)	8.0 (0.5)	5.9 (2.0)**	10.5 (2.7)**
	Control Sample	1.10 (0.08)	8.3 (0.3)**	7.4 (0.6)**	11.6 (1.5)**
	Historic Field	1.23 (0.16)***	8.2 (0.3)	6.4 (2.4)**	12.8 (4.9)**
Pleistocene Terrace	Prehistoric Field	1.16 (0.11)**	8.1 (0.5)	6.7 (1.1)	12.1 (1.6)
	Control Sample	1.29 (0.11)	8.2 (0.1)	5.4 (0.1)**	9.0 (1.2)**
	Historic Field	1.27 (0.07)	7.9 (0.3)	6.5 (0.7)	13.4 (1.5)

Note. Data are means (standard deviations in parentheses) for 18 sampling sites.
One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* p < 0.10, ** p < 0.05 , *** p < 0.01 (stars indicate different from other field contexts within the same geomorphic surface)

Geomorphic Surface		Ammonium (mg N/kg soil)	Nitrate (mg N/kg soil)	% Soil Moisture
Holocene Terrace	Prehistoric Field	2.29 (2.11)	52.98 (98.38)	3.89 (1.96)
	Control Sample	1.88 (2.44)	29.86 (35.96)	3.75 (0.83)
	Historic Field	2.39 (3.54)	64.86 (98.29)	3.85 (1.84)
Pleistocene Terrace	Prehistoric Field	3.06 (2.60)	80.42 (118.93)	2.92 (1.03)
	Control Sample	4.49 (0.75)	5.40 (1.49)	1.80 (0.23)**
	Historic Field	4.36 (3.75)	114.22 (76.51)	2.49 (0.25)

Note. Data are means (standard deviations in parentheses) for 18 sampling sites.
One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate different from other field contexts within the same geomorphic surface.

Table 6.3: Significant Differences in Soil Characteristics among Fields and Control Samples. Blank Cell Indicates no Significant Difference Among Categories (e.g., if cells from both prehistoric fields and historic fields are blank, no statistically significant difference exists between them)

	Prehistoric Fields	**Control Samples**	**Historic Fields**	**Enhancement or Degradation of Soils?**	**Comments**
Characteristics Essential for Successful Plant Cultivation					
% Clay		Lower than all fields		Enhancement in All Fields	Pleistocene Terrace Only
% Silt		Higher than all fields		Mixed by Geomorphic Context	Holocene Terrace
		Lower than all fields			Pleistocene Terrace
% Sand		Lower than all fields		Mixed by Geomorphic Context	Holocene Terrace
		Higher than all fields			Higher on Pleistocene Terrace
Organic Carbon (g C/kg soil)	Higher than control, lower than historic fields	Lower than all fields	Higher than prehistoric fields	Enhancement in All Fields	All Geomorphic Contexts
Total Nitrogen (g N/kg soil)	Lower than historic fields, higher than controls	Lower than all fields	Higher than control samples and prehistoric fields	Enhancement in All Fields	All Geomorphic Contexts

Electrical Conductivity (dS/m)	Higher than control samples and historic fields			Degradation in Prehistoric Fields	Holocene Terrace Only (skewed by one sampling site – GR 782)
Sodium Adsorption Ratio			Lower than prehistoric fields and control samples	Enhancement (Historic Fields Only) in one Geomorphic Context	Holocene Terrace Only
Available Phosphorus (mg P/kg soil)		Lower than all fields		Enhancement in one Geomorphic Context	Holocene Terrace Only
Characteristics Less Important for Successful Plant Cultivation					
Bulk Density			Higher than control and prehistoric fields	No major effects on crop productivity	Holocene Terrace Only
pH		Higher than all fields		No major effects on crop productivity	Holocene Terrace Only
Inorganic Carbon (g/kg)	Lower than control samples and historic fields	Higher than all fields	Higher than prehistoric fields	No major effects on crop productivity	Holocene Terrace
		Lower than all fields			Pleistocene Terrace
Total Carbon (g C/kg soil)	Lower than control samples and historic	Higher than prehistoric fields	Higher than control samples	No major effects on crop productivity	Holocene Terrace

	fields	only	and prehistoric fields		
	Higher than control samples only	Lower than all fields	Higher than control samples and prehistoric fields		Pleistocene Terrace
Nitrate (mg N/kg soil)					No significant differences
Ammonium (mg N/kg soil)					No significant differences
% Soil Moisture		Lower than all fields		No major effects on crop productivity	Pleistocene Terrace Only

Characteristics Essential for Successful Plant Cultivation. Soil characteristics, such as carbon (organic), nitrogen (total), and available phosphorus, are essential to the growth of maize and wheat, and their reduction has been noted in some prehistoric dryland fields across the U.S. Southwest (e.g., Sandor and Gersper 1988). Additionally, the physical characteristics of the soil, including soil texture (% clay, silt, and sand), provide important insights into how well water and roots can infiltrate the soil. Fine sediments are particularly important in arid soils created in alluvial environments, which can be coarse and high in sands that allow water to percolate through the soil too quickly and are low in nutrients. Fine sediments retain water for longer periods of time making water more available to crops and are frequently higher in nutrients due to their larger surface area. Perhaps most importantly in an irrigated system, electrical conductivity and sodium adsorption ratio provide insight into added salts and sodium, which can greatly stunt crop growth in high quantities in irrigated fields.

For all fields compared to landscape controls, 2 out of 8 essential characteristics demonstrate enhancement in prehistoric and historic fields in all geomorphic contexts (organic carbon and total nitrogen), 3 out of 8 characteristics were enhanced in only one geomorphic context (% clay, SAR, and available phosphorus), 2 out of 8 characteristics saw mixed effects in all fields (% silt and % sand), and 1 characteristic essential for understanding plant cultivation demonstrates a degraded state in prehistoric fields in one geomorphic context (electrical conductivity).

When comparing historic fields to prehistoric fields to assess how the intensification of agriculture affected soils, historic fields were enhanced in 2 out of the 8 characteristics (organic carbon and nitrogen) more than prehistoric fields. Sodium adsorption ratio was enhanced in historic fields over prehistoric fields in one geomorphic context. All other characteristics (soil texture, electrical conductivity, and available phosphorus) were not significantly different between historic and prehistoric fields.

Texturally, the agricultural fields are significantly higher in percent clay, but percent silt numbers vary (Figure 6.1a and 6.1b). Fields on the Pleistocene Terrace exhibit higher silt percentages than the controls, but this is not the case on the Holocene Terrace. While less silt in agricultural fields on the Holocene Terrace may indicate that silt was not added by irrigation, I believe that this is a function of the control sampling site (GR 643), which is higher in silt than other parts of the landscape, thus artificially elevating our understanding of the overall “natural landscape” of the middle Gila River. No differences in silts and clays, however, exist between prehistoric and historic fields.

One of the main effects of long-term irrigation on soil quality is the addition of various salts to the soils. Because salinization has been a significant focus of hypotheses concerning the collapse of many civilizations that irrigated their agricultural fields (e.g., Mesopotamia, coastal Peru, and the Hohokam), measuring the amount of salt in the soil of the sampled agricultural fields was of particular interest for this analysis. Electrical conductivity (dS/m) is the main analysis that quantifies the amount of salinity in the soil.

Alkalinity is also an issue for irrigated soils and has been frequently mentioned as a problem in fields farmed in the study area after the loss of water in the late AD 1800s and early AD 1900s, so it likely would have been an issue that prehistoric and historic farmers would have had to address in times of low streamflow (Southworth 1919). To measure alkalinity, or sodium carbonate, in the soils, the Sodium Adsorption Ratio is calculated from the proportion of sodium to calcium and magnesium in the soil. Figure 6.2 shows the classification of saline and sodic soils by Electrical Conductivity and Sodium Adsorption Ratio and the classification's relationship to crop tolerances. pHs across the sampled agricultural fields are, on average, less than 8.5.

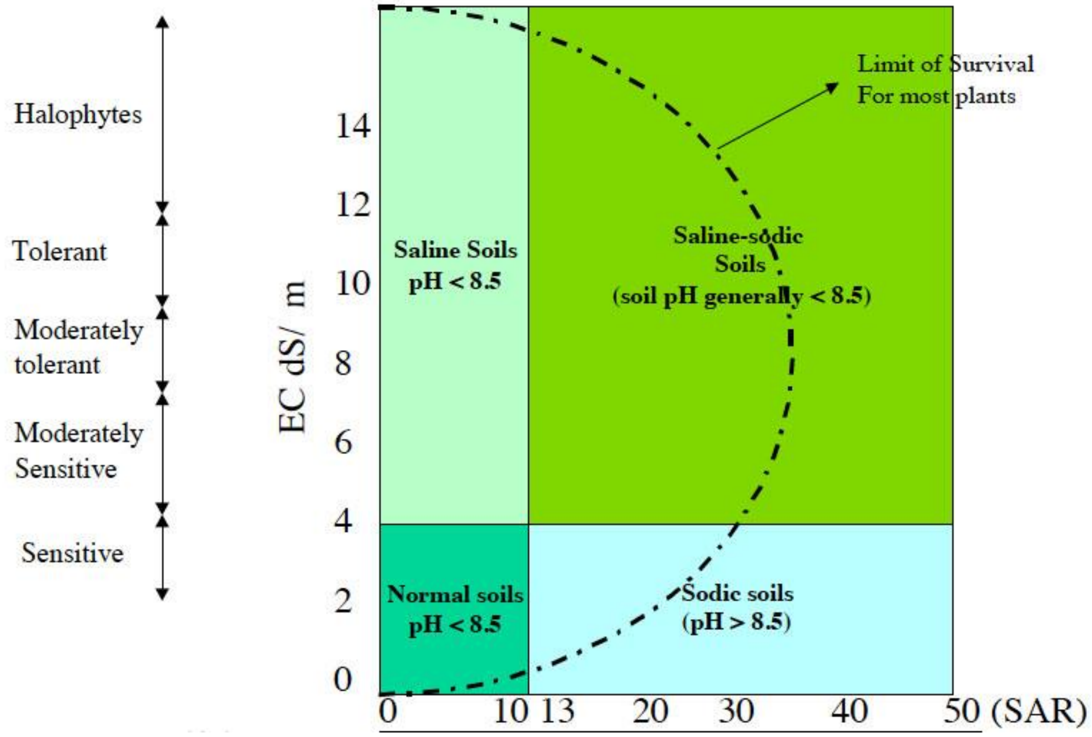


Figure 6.2: Levels of Salinity and Alkalinity in Soil and Their Effects on Crop Productivity

Figures 6.1f and 6.1g show the average electrical conductivity and sodium adsorption ratio by time period of use and geomorphology and indicate degradation in prehistoric fields in one geomorphic context and enhancement in historic fields in one geomorphic context. The results on electrical conductivity show mixed signs of degradation with prehistoric fields in one geomorphic context higher in EC than historic fields and control samples. The higher electrical conductivity in prehistoric fields, however, is largely being driven by one sampling site – GR 782 – that has average electrical conductivities approaching 50 dS/m, thus driving the numbers of electrical conductivity in prehistoric fields artificially high. Thus, salinity levels are largely within the acceptable range of production for most crops across the middle Gila River, except at one prehistoric field at GR 782.

The sodium adsorption ratio (SAR) data indicate that alkalization was likely not a problem in prehistoric or historic fields and SAR is significantly lower in historic fields than prehistoric fields and control samples on the Holocene Terrace.

Characteristics Less Important for Successful Plant Cultivation. Certain soil characteristics were analyzed to ensure that numbers were within range for cultivation on the middle Gila River and to understand the relationship of soil characteristics to soil formation. pH, a measure of soil acidity or alkalinity, can control the availability of many nutrients to plants by restricting how nutrient ions can be exchanged by soil particles. The optimal pH for most plants worldwide is between 5.5 and 7.0, although many plants, including those in the Sonoran desert, have adapted to thrive outside of that range. Levels of pH (Figures 6.1j) are consistent between prehistoric and historic fields, but all fields are significantly lower in pH than control samples on the Holocene Terrace. All average pH levels are slightly alkaline, but within the range of normal for soils expected for the middle Gila River and would likely not affect crop production (Sandor 2010).

Bulk density (Figure 6.1i) measures soil compaction and the ability for roots and water to infiltrate soils. As bulk density reaches levels of 1.5 g/cm^3, compaction can become a problem in loamy soils, like those on the GRIC, restricting root and water infiltration. Bulk density is significantly higher in historic fields than prehistoric fields and control samples on the Holocene Terrace, but average bulk densities do not reach levels that would inhibit cultivation. Average bulk densities around 1.2 g/cm^3 in all contexts indicate conditions ideal for cultivation.

Inorganic carbon is not a plant nutrient, but can control pH and alkalinity of soils in high levels. All fields are significantly higher in inorganic carbon than control samples on the Pleistocene Terrace (Figure 6.1k). On the Holocene Terrace, all fields are significantly lower in inorganic carbon, and historic fields are significantly higher than the prehistoric fields, but these levels would not affect agricultural production. Total carbon is significantly higher in all historic fields, while it is lower in control samples than all fields on the Pleistocene Terrace. On the Holocene Terrace, soils from the prehistoric fields were significantly lower in total carbon than both the control samples and historic fields. No significant differences were measured in available nitrogen – ammonium and nitrate. From these results, it is clear that geomorphic context is a main driving factor of soil characteristics on the middle Gila River, in addition to prehistoric and historic irrigation.

Assessing Research Theme 1: Evaluating the Influence of the Longevity of Irrigation on Soil Quality

It appears that the longevity of irrigation resulted mostly in enhancement of soils. All fields, including both prehistoric and historic fields, benefitted from long-term irrigation with the addition of organic carbon and total nitrogen, indicating that long-term irrigation added nutrients to the soil through the addition of water and sediments (see below for a discussion of evidence for sedimentation) (Tables 6.3, 6.4). Other indicators, including soil texture, are also largely enhanced but not in both geomorphic contexts. These results may be due to a lack of appropriate control samples, which has always been a problem in sampling landscapes of long-term and widespread anthropogenic activity (Sandor and Homburg 2010).

Management of Salinity and Alkalinity. Perhaps most importantly in irrigated fields is the management of salinity. From the levels of electrical conductivity presented above, it appears that salinity was largely controlled in all agricultural fields, with the exception of one prehistoric field at GR 782. These numbers indicate that while irrigation added salts to the soil, extremely high levels of salinity in the soil were highly localized, and were not a pervasive problem across the prehistoric and historic fields along the middle Gila River (Tables 6.2 and 6.3).

Because moderate amounts of salts were added to the field soils by long-term irrigation, it is important to consider the effects these added salts may have had on specific crops. While tolerances to salinity of native varieties of crops growing prehistorically and historically have not been measured, the tolerances of modern varieties of crops to salts can shed light onto how they may have been differentially affected by the buildup of salts in the soil. Cotton and wheat are generally salt-tolerant, maize can be sensitive to soil salinity. Yield reduction of maize can occur at electrical conductivity levels at 1.7 dS/m, which is below the measured electrical conductivity levels across the study area, including landscape controls (Ayers 1977). While levels of electrical conductivity indicate that levels of salinity along the middle Gila River may affect the production of modern maize, archaeological, ethnographic, and historic evidence indicates that salinity did not impact the production of maize along the middle Gila River in the prehistoric or historic periods, which encompass over 1000 years of cultivation. This evidence is corroborated by ethnographic data from interviews of O'odham farmers, who rarely mentioned salinity. For instance, Has Makil, farming land near Sacaton, said, "We Pimas… knowing how to deal with alkali with long experience, soon made these spots fertile farms" (DeJong 2011:58).

It is possible that locally adapted strains of maize were tolerant of the slightly elevated levels of salinity in the soil. Wheat and cotton yields, however, are not affected below an electrical conductivity of 6.0 dS/m and 7.7 dS/m, respectively, which are also within the ranges of electrical conductivity of some soils sampled across the GRIC. From these ethnographic observations, it is likely that native varieties of maize and cotton were adapted to local conditions along the middle Gila River, which included soils that were naturally high in salt and sodium.

Low Nutrient Levels and Evidence for Sedimentation. Overall, the soils on the middle Gila River are low in total nitrogen (~0.50 g N / kg soil) and available phosphorus (~3.32 mg P / kg soil) to the extent that they would limit agricultural crop production. These numbers indicate that additions of nutrients in the past would have been necessary to maintain agricultural production, but, due to the lack of large animals prehistorically on the middle Gila River, fertilization from animal dung was not possible. Sedimentation, then, would have been the best source for the addition of nutrients to these otherwise nutrient-poor soils.

Previous analyses of prehistoric Hohokam fields have shown that sedimentation occurred, unintentionally and intentionally, in different parts of the Phoenix Basin, including Queen Creek and Cave Creek (Huckleberry 2011; Schaafsma and Briggs 2007). Sedimentation can have both positive and negative effects on the soil either by adding nutrients, silts, and organic matter to these arid soils or by burying seedlings or canal headgates, resulting in the destruction of crops. Across the middle Gila River, sedimentation appears to be the key factor in maintaining soil quality with long-term irrigation.

The general depth and thickness of agricultural field strata sampled across the Gila River Indian Community are listed in Table 6.4. These data indicate that prehistoric fields are located deeper than historic fields, likely due to their older age, due to ongoing soil development and longer periods of sedimentation from flooding and irrigation. The mean addition of sediments, however, is similar across both prehistoric and historic agricultural fields. Although fields in general are quite variable in their thickness (see Appendix A for details on strata from each sampled site), these agricultural strata are over 30 cm thick on average, which represents a large anthropogenic addition of sediments to the soil profile. As noted above, these sediments added nutrients essential to crop productivity.

The Natural Resources Conservation Service likely observed these buried anthropogenic horizons, but did not define them as such (Figures 6.3 and 6.4), describing “soil ribbons” in association with prehistoric and historic canal systems in their soil survey for the middle Gila River (Johnson et al. 2002). These soil ribbons are fine laminations of sediments added by irrigation water (Figure 6.3 and 6.4). These observations suggest that buried soils are present in many areas along the middle Gila River and related to long-term irrigation. While not defined as such by the NRCS, these soils have been so greatly altered by long-term irrigation that they could be defined as ***irragric Anthrosols*** (IUSS 2006).

Table 6.4: Mean Thickness and Depth of Agricultural Field Strata

Time of Use	**Mean Depth of Field Below Surface (cm)**	**Mean Addition of Anthropogenic Stratum (cm)**
Prehistoric Field	38.9	31.6
Historic Field	29.3	30.7

Figure 6.3: Soil Profile of GR 1528. Irrigated field sediments can be observed between 20 and 40 cm on the Measuring Tape.

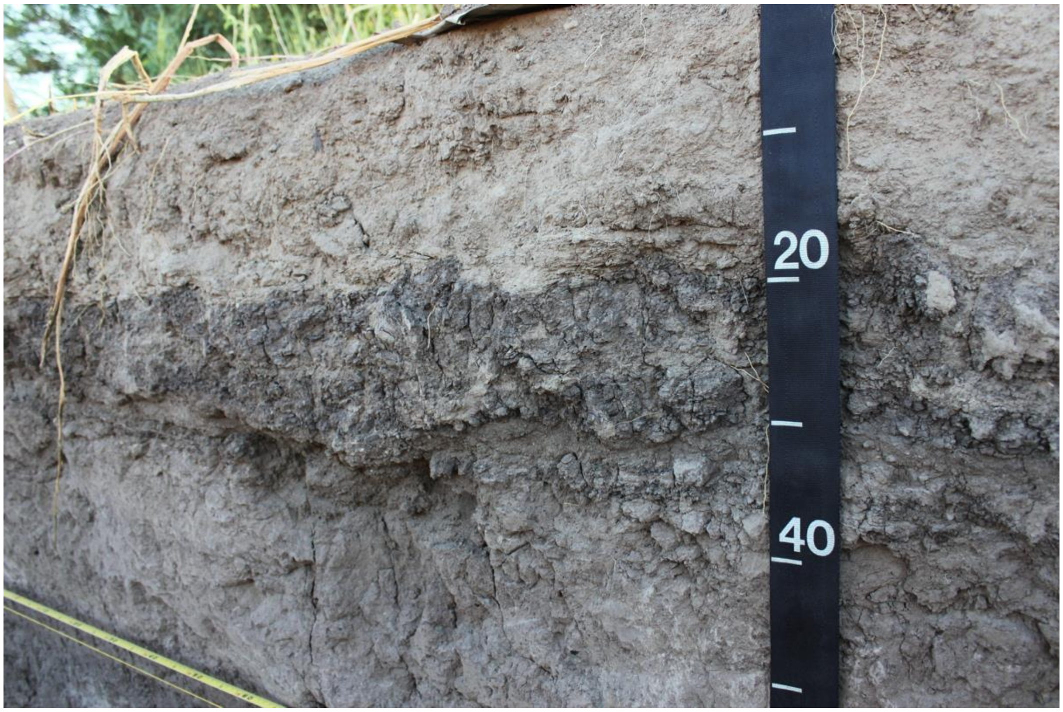


Figure 6.4: Close up of irrigated field sediments in the soil profile of GR-1528.

The importance of sedimentation in the maintenance and enhancement of soil quality has been mentioned in multiple ethnographies of the O'odham (Castetter & Bell 1942; DeJong 2011; Russell 1908). Castetter and Bell (1942), for instance, argue, "The fact that many of the Piman fields have been under cultivation for hundreds of years, producing sustained crop yields without the addition of manures or other fertilizers, is evidence that considerable plant nutrients were carried by the waters used for irrigation in the Gila Basin" (1942: 172). The importance of the addition of irrigation water was reiterated in interviews with O'odham farmers in AD 1914, when they could no longer incorporate this strategy into their agricultural system due to the loss of water along the middle Gila River in the late AD 1800s (Southworth 1919). While most of the interviews focused on the pressing issue of the lack of water, some farmers spoke about the improvement of fields with the addition of irrigation water. One farmer went so far as to refer to irrigation water as a fertilizer, saying, “As to fertilizing our farms, we do not have to use any fertilizer, soil is rich except in some districts where there is alkali, then flood water is needed to fertilize it” (DeJong 2011: 85). Another farmer, however, stressed the negative impact of sedimentation, which cannot be measured with the data collected for this dissertation. George Pablo recounted the destruction of canal headings, saying “the flood water coming down cut through this diversion [canal ditch], destroying this diversion or heading of the slough with deposits of silt” (DeJong 2011: 71). These observations indicate the importance of sedimentation in the maintenance of soil quality, but caution that sedimentation can lead to destructive consequences for agricultural productivity if not properly controlled.

Assessing Research Theme 2: Evaluating the Impact of the Intensification of Irrigation Agriculture on Soil Quality on the Middle Gila River

The intensification of agriculture on the middle Gila River resulted in enhancement in 2 out of 7 characteristics essential for crop production (organic carbon and total nitrogen) in historic fields (compared to less intensively used prehistoric fields). Additionally, the sodium adsorption ratio is lower in historic than in prehistoric fields on the Holocene Terrace, indicating that sodium was better managed during this time, as well. None of the essential characteristics of historic fields are degraded with respect to either the controls or the prehistoric fields.

These improved chemical characteristics of the soil in historic fields are likely due to the addition of more irrigation water from the canals as production intensified in the historic period. With the intensification of agriculture at this time, an additional crop was added to the agricultural calendar – wheat during the winter months. With this additional crop, more water was added to the fields during months – December through March - that were likely not irrigated prehistorically. Thus, additional irrigation water carrying sediments may have added nutrients essential to the soil, improving soil quality in fields used historically, and likely helped leach soils of accumulating sodium.

Soil Results from the North Coast of Peru

General Soil Characteristics

Overall, the soil characteristics reflect those typical of an arid environment and are similar to the characteristic of soils reported in a previous study of agricultural soils on the Pampa de Chaparrí (Nordt et al. 2004). Table 6.5 displays the means and standard deviations for all soil tests done on agricultural soils throughout the Pampa. The soils on the Pampa are generally low in total and available nitrogen, and soil organic matter, and have moderate levels of salinity and alkalinity. The soils are coarse-textured (sands are generally over 50% and clays compose about 10% of the particle size distribution), which may prevent salts from accumulating, but also lead to lower nutrient levels. Like the middle Gila River, the pH of the soil is moderately alkaline (~ 8.1), which would not limit agricultural productivity (Brady and Weil 2008). These characteristics of the soils indicate that while salinity and alkalinity may have been controlled by the naturally coarse texture of the soil, inputs of nitrogen and organic matter would have been necessary in the past to maintain agricultural production over the long-term.

Table 6.5: General Soil Characteristics from the Pampa de Chaparrí (N=225)

	Mean	**Std. Deviation**
Characteristics Essential for Successful Plant Cultivation		
% Clay	10.0	3.5
% Silt	36.1	9.8
% Sand	53.9	11.7
% Coarse Fragments	16.2	8.0
Possible Organic Matter Loss on Ignition (%)	2.22	0.78
Total Nitrogen (g N/kg soil)	0.59	0.20
Electrical Conductivity (dS/m)	7.0	3.6
Sodium Adsorption Ratio	1.5	0.9
Available Phosphorus (mg P/kg soil)	11.73	6.47
Characteristics Less Important for Successful Plant Cultivation		
Bulk Density (g/cm^3)	1.46	0.14
pH	8.1	0.2
Total Carbon (g C/kg soil)	5.8	2.3
Nitrate (mg N/kg soil)	7.9	14.2
Ammonium (mg N/kg soil)	0.9	2.8
% Soil Moisture	1.47	0.72

Assessing Research Themes 1 and 2: on the North Coast of Peru – The Relationship between the Longevity and Intensification of Irrigation Agriculture and Soil Quality

In order to address both research themes, soils from agricultural fields on the Pampa were collected to understand how fields were affected by and maintained for 600 years of prehispanic use. Because of the diversity in field types observed throughout the Pampa, the collection strategy and analysis differs from that of the middle Gila River (see Table 6.6 for a description of how each research theme is addressed). The effects on soils from the longevity of irrigation agriculture can be observed in number of different ways. First, the differences between ridges and furrows are analyzed to understand how ridges were used to increase soil quality in the furrows, where the crops were planted. Second, potential solutions to the overall total low nitrogen on the Pampa are explored to understand how agricultural productivity could have been maintained. It is likely that, like the middle Gila River, sedimentation from irrigation water would have been an important source of valuable nutrients and organic matter to the soil. Thus, highly localized contexts on the Pampa de Chaparrí – waffle gardens and an anthropogenic deposit – indicate that sedimentation did indeed occur on the Pampa prehispanically.

To assess how the intensification of agriculture affected soils on the Pampa de Chaparrí, soils from state-controlled walled fields are compared to soils from agricultural fields outside of the walled areas that were less intensively farmed. As explained in Chapters 2 and 4, some researchers have argued that these walled fields indicate state-level control (Kolata 1990; Moseley and Day 1982; Téllez and Hayashida 2004). If these walled fields were indeed under the control of state-level forces, they may have been more intensively cultivated in order to produce a surplus to support elites (see Chapter 2). Two different walled fields were sampled on the Pampa, and soils from adjacent unwalled areas are compared to the soils from walled fields. These two different walled field areas were analyzed separately because they are located in different geomorphic contexts.

Table 6.6: Research Themes and How They Are Addressed with Data from the Pampa de Chaparrí

Research Theme	**How Analyzed**	**Hypothesis**
Longevity	Ridges and Furrows are compared to clarify how salts are managed across the Pampa	In raised field beds, the ridges are frequently used to draw salts away from the planting surfaces (furrows). It is hypothesized that ridges will be lower in soil quality, especially concerning salinity, to maintain higher soil quality in the furrows.
	Examine how overall low total nitrogen was combatted across the Pampa	Potential inputs for nitrogen are explored, and it is hypothesized that sedimentation would have been the likely process to add the needed total nitrogen to the soil.
	Evidence for Sedimentation in Waffle Gardens and the Anthropogenic Deposit	If sedimentation was important across the Pampa, different localized contexts are provided as potential evidence that sedimentation did occur prehispanically.
Intensification	Walled Field Area 1 is Compared to Two Adjacent Unwalled Areas	Two different walled field areas are analyzed separately due to geomorphic differences between them. It is hypothesized that the

	Walled Field Area 2 is Compared to One Adjacent Unwalled Area	walled fields are more heavily degraded than the adjacent unwalled areas due to their more intensive use in the past.

Differences in Soil Quality between Ridges and Furrows

Because prehispanic fields are visible at the surface on the Pampa, the differences in soils between the ridges and furrows can be compared to understand if specific parts of the fields are differentially affected by long-term irrigation. The furrows are used to deliver water from the distributory canals to the fields, while ethnographic data on agriculture in the region today indicate that both the sides of the ridges and the furrows can be used as planting surfaces for a variety of crops (Erickson 2003). While some researchers have argued that salinity would have been naturally controlled due to the coarse texture of soils on the Pampa (Nordt et al. 2004), irrigation water likely added salts to the soils that farmers would have had to control over the long-term.

Across the entire Pampa, interesting differences can be seen between the ridges and the furrows (Table 6.7). The furrows are significantly enhanced in 4 out of the 9 soil characteristics important for plant cultivation. The furrows are significantly higher in total nitrogen and available phosphorus and significantly lower in electrical conductivity and sodium adsorption ratio. In the 6 characteristics less important to plant cultivation, results are mixed. Furrows are enhanced in total carbon, and ridges are enhanced in nitrate. No significant differences are observed in ammonium, soil texture, pH, soil moisture, soil organic matter loss on ignition, bulk density, and coarse fragments. Thus, nutrients important to agricultural production, like total nitrogen and available phosphorus, accumulated in the furrows, while salinity and alkalinity are higher in the ridges.

Table 6.7: Differences in Ridges and Furrows in All Field Areas Across the Pampa de Chaparrí (n = 113 for both ridges and furrows)

						Independent Samples T-Test Results		
		Mean	Std. Deviation	Where Significantly different?	Enhancement or Degradation?	T	df	2-tailed Significance
Characteristics Essential for Successful Plant Cultivation								
% Clay	furrow	9.8	3.6			-.821	214	.413
	ridge	10.2	3.4					
% Silt	furrow	35.7	9.5			-.548	214	.584
	ridge	36.4	10.2					
% Sand	furrow	54.5	11.4			.708	214	.480
	ridge	53.4	12.0					
% Coarse Fragments	furrow	15.6	8.0			-1.074	218	.284
	ridge	16.8	8.0					
Organic Matter Loss on Ignition (%)	furrow	2.29	0.86			1.406	222	.161
	ridge	2.15	0.69					
Total Nitrogen (g N/kg soil) ***	furrow	0.66	0.22	Higher in furrows	Enhancement in Furrows	5.742	223	.000
	ridge	0.52	0.13					
Electrical	furrow	5.6	1.7	Higher in ridges	Degradation in	-6.386	216	.000

Conductivity (dS/m) ***	ridge	8.4	4.3		Ridges			
Sodium Adsorption Ratio ***	furrow	1.2	0.7	Higher in ridges	Degradation in Ridges	-4.462	218	.000
	ridge	1.8	1.1					
Available Phosphorus (mg P/kg soil) ***	furrow	14.0	6.6	Higher in furrows	Enhancement in Furrows	5.774	223	.000
	ridge	9.4	5.5					
Characteristics Less Important for Successful Plant Cultivation								
Bulk Density (g/cm^3)	furrow	1.45	0.14			-1.150	221	.251
	ridge	1.47	0.14					
pH	furrow	8.1	0.2			-1.459	218	.146
	ridge	8.2	0.2					
Total Carbon (g C/kg soil) ***	furrow	6.4	2.6	Higher in furrows	Enhancement in Furrows	3.727	223	.000
	ridge	5.3	1.8					
Ammonium (mg N/kg soil)	furrow	0.88	0.67			-.108	223	.914
	ridge	0.92	3.93					
Nitrate (mg N/kg soil) ***	furrow	4.08	7.78	Higher in ridges	Enhancement in Ridges	-4.258	223	.000
	ridge	11.83	17.71					
% Soil Moisture	furrow	1.47	0.68			.025	223	.980
	ridge	1.47	0.75					

Note. Data are means (standard deviations in parentheses) from all field areas.
Independent Samples T-Tests were run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate ridges and furrows are significantly different)

Intensively Used Walled Field Areas

Soils from two different walled field areas were sampled and compared to non-walled fields directly adjacent to and outside of the walled fields. Figure 6.5a-o provides box plots and Tables 6.8 and 6.9 show the ANOVA results of the statistical analysis for both walled field areas and their adjacent unwalled agricultural areas.

Walled Field Area 1. In the first location (Area 1), results between unwalled and walled fields are mixed. Statistically measurable differences emerge in 6 out of the 9 soil characteristics important for plant cultivation. Enhancement in the walled field is seen in SAR (lower in walled field), available phosphorus (higher in walled field) and total nitrogen (higher in walled field). Mixed results are seen in % silt (lower in one unwalled field) and % sand (lower in one unwalled field). Degradation in the walled field is observed in % coarse fragments in the soil (higher in walled field). In less important characteristics to plant cultivation, significant differences are evident in total carbon (lower in one unwalled field), pH (lower in one unwalled field), nitrate (higher in one unwalled field), but none are degraded or enhanced enough to affect plant cultivation. No measurable differences are observed among the walled and unwalled field areas in electrical conductivity, ammonium, % clay, bulk density, soil moisture, and organic matter loss on ignition (Figure 6.5, Table 6.8).

This area shows mixed results concerning whether soils within the walled field were affected by the intensification of agriculture. Because phosphorus and nitrogen particles are frequently associated with finer particles in soil, the concurrence of both higher available phosphorus and coarse particles (both coarse fragments and sand are higher within the walled field) may indicate higher levels of wind erosion within the walled field when compared to the unwalled fields. More research is needed to clarify this erosional process, but it is possible that prehispanic degradation of soils may have affected the regrowth of vegetation after abandonment, leading to higher levels of wind and water erosion. For example, if this walled field was more degraded after abandonment, vegetation may not have grown back as quickly, resulting in legacy effects in the soil, such as increased erosion, which carries fine sediments away from the field, artificially elevating associated nutrients.

Walled Field Area 2. Unlike in the first walled field area, the second walled field area shows measurable differences in many soil characteristics important to crop cultivation (Figure 6.6; Table 6.9). The walled field is degraded in 6 out of 9 characteristics essential to plant cultivation, including % clay (lower in walled field), % silt (lower in walled field), % sand (higher in walled field), % coarse fragments (higher in walled fields), organic matter loss on ignition (lower in walled field), and total nitrogen (lower in walled field). In less essential characteristics, this walled field is significantly higher than the unwalled field in bulk density (and approaching levels that could affect crop cultivation at 1.56 g/cm^3), and significantly lower that the unwalled field in ammonium, pH, nitrate, % soil moisture, and total carbon. No significant differences between the walled field and unwalled field in Area 2 are measurable in electrical conductivity, SAR, and available phosphorus.

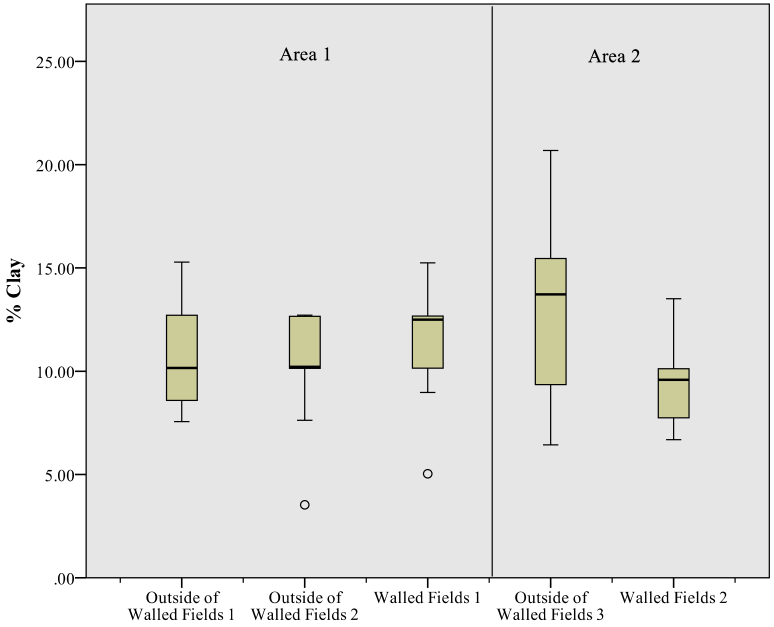


Figure 6.5a: % Clay. % Clay is significantly higher in the unwalled field in Area 2.

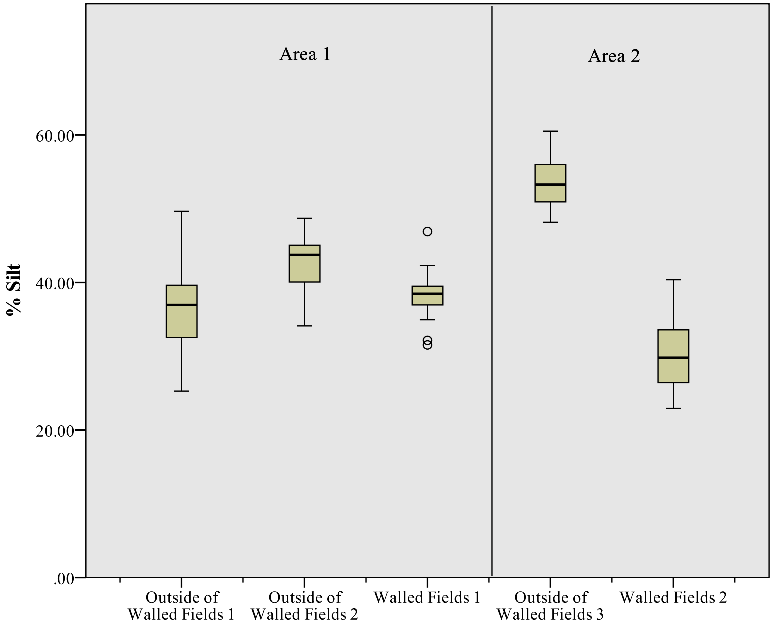


Figure 6.5b: % Silt. % Silt is significantly lower in one unwalled field in Area 1 and significantly higher in the unwalled field in Area 2.

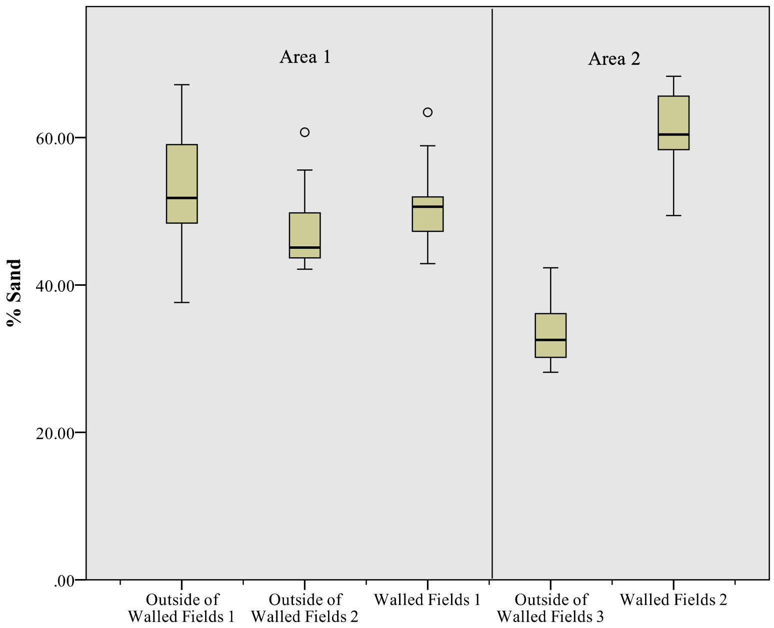


Figure 6.5c: % Sand. % Sand is significantly higher in one unwalled field in Area 1 and higher in the walled field in Area 2.

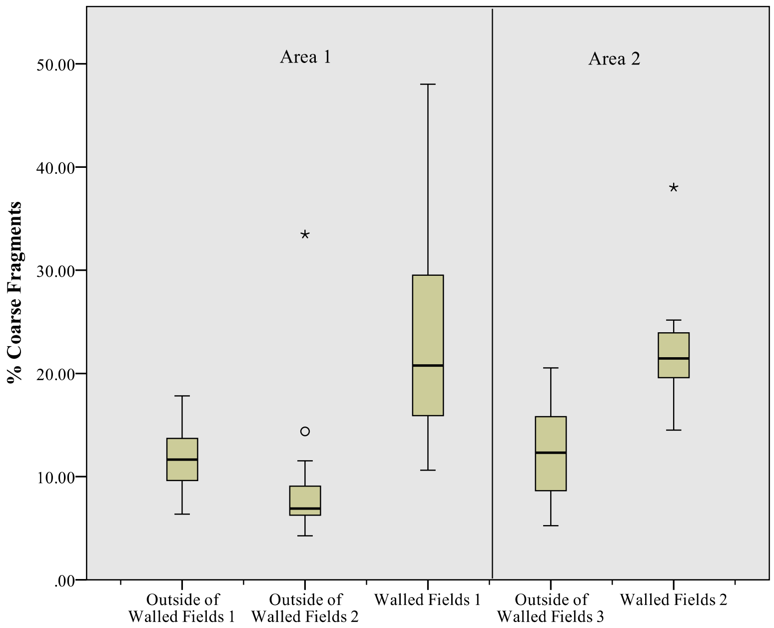


Figure 6.5d: % Coarse Fragments. Coarse fragments are significantly higher in the walled field in Area 1 and significantly lower in the unwalled field in Area 2.

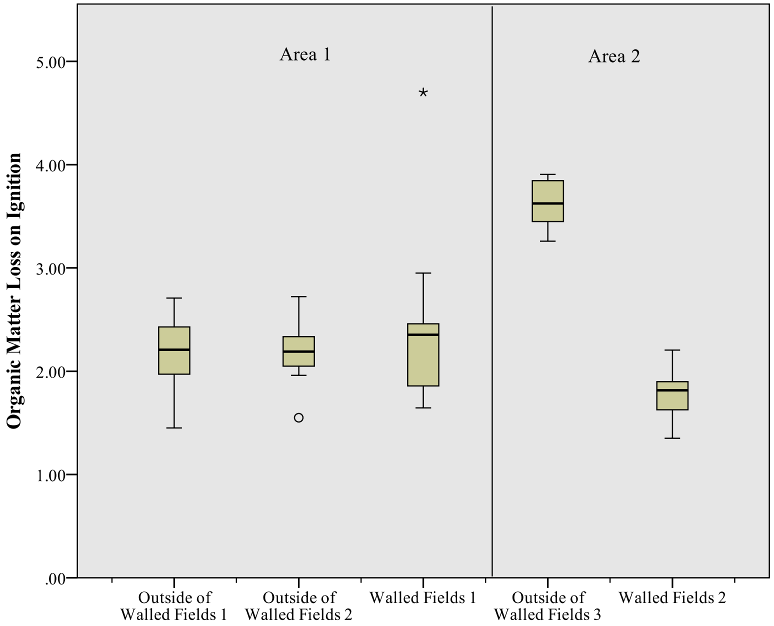


Figure 6.5e: Organic Matter Loss on Ignition (%). Organic matter loss on ignition is significantly lower in the walled field in Area 2.

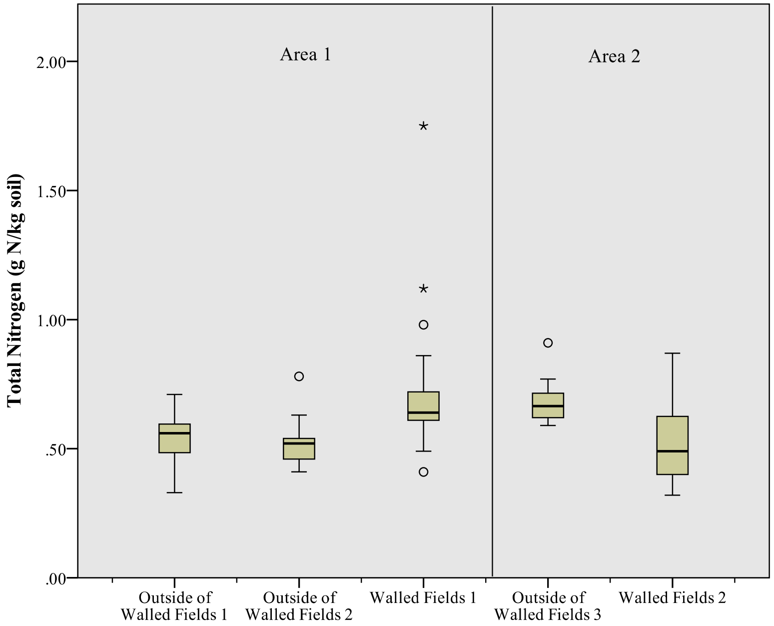


Figure 6.5f: Total Nitrogen. Total Nitrogen is significantly higher in the walled field in Area 1 and significantly lower in the walled field in Area 2.

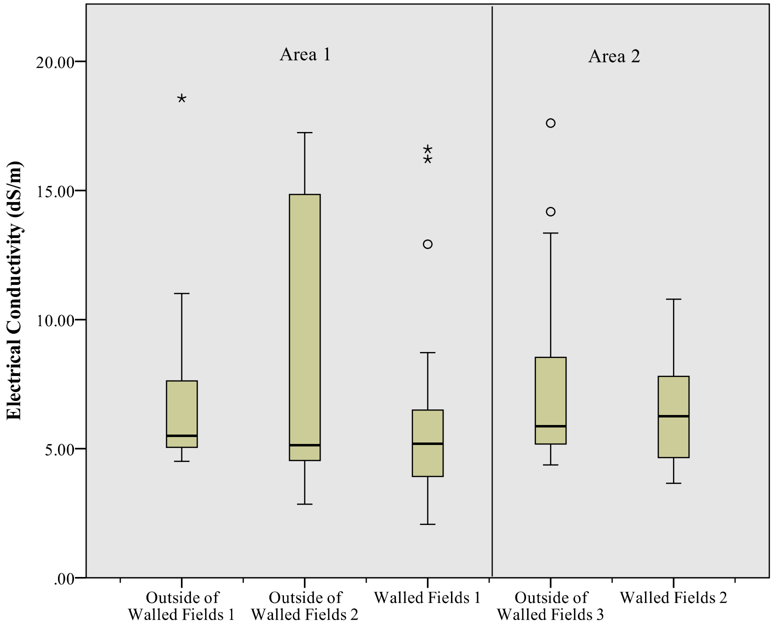


Figure 6.5g: Average Electrical Conductivity. No significant differences.

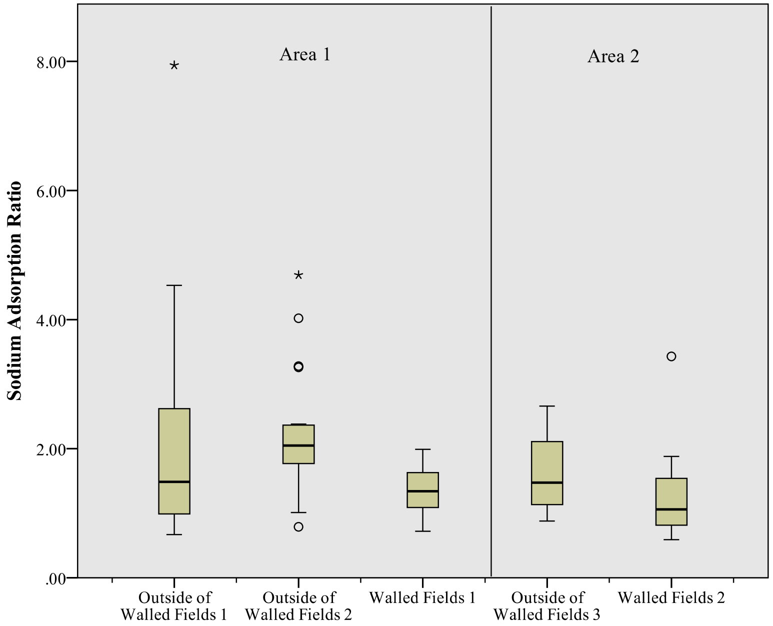


Figure 6.5h: Sodium Adsorption Ratio. SAR is significantly lower in walled field in Area 1.

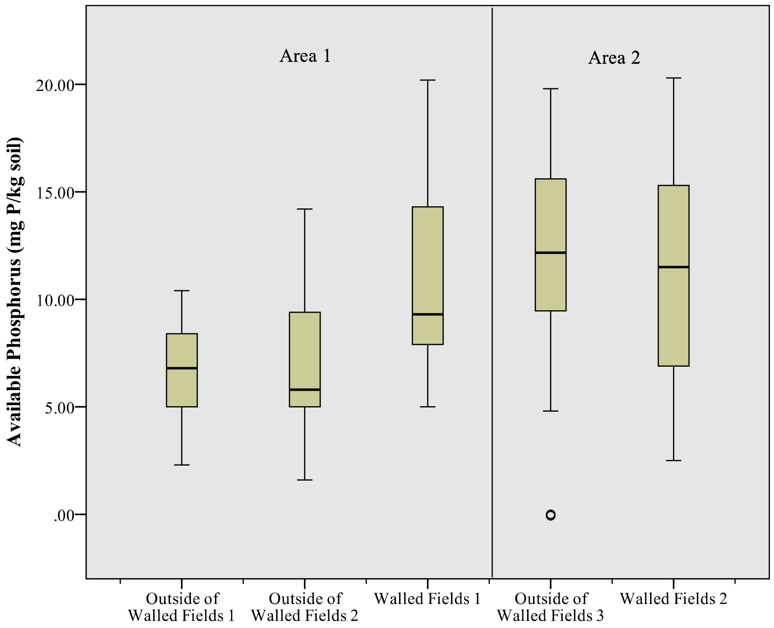


Figure 6.5i: Available Phosphorus. Available phosphorus is significantly higher in the walled field in Area 1.

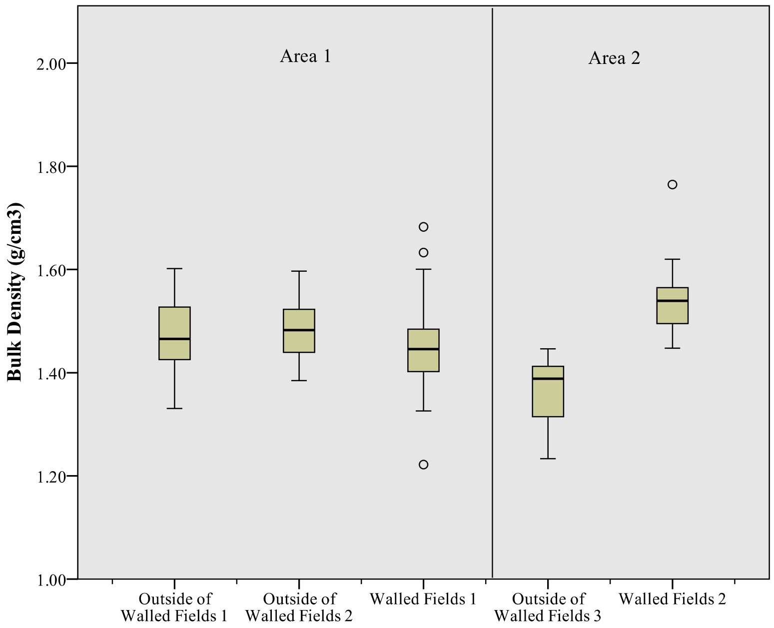


Figure 6.5j: Bulk Density. Bulk Density is significantly higher in the walled field in Area 2.

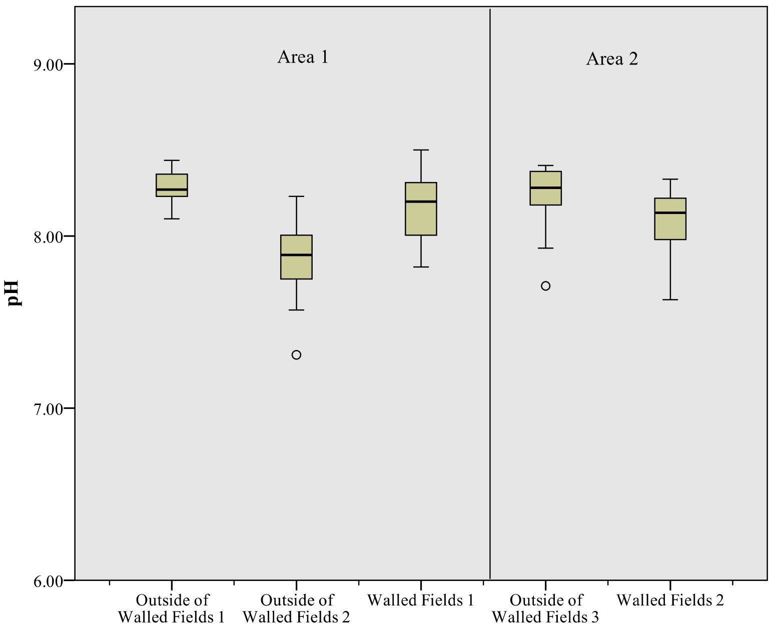


Figure 6.5k: pH. pH is significantly lower in one unwalled field in Area 1 and significantly higher in unwalled field in Area 2.

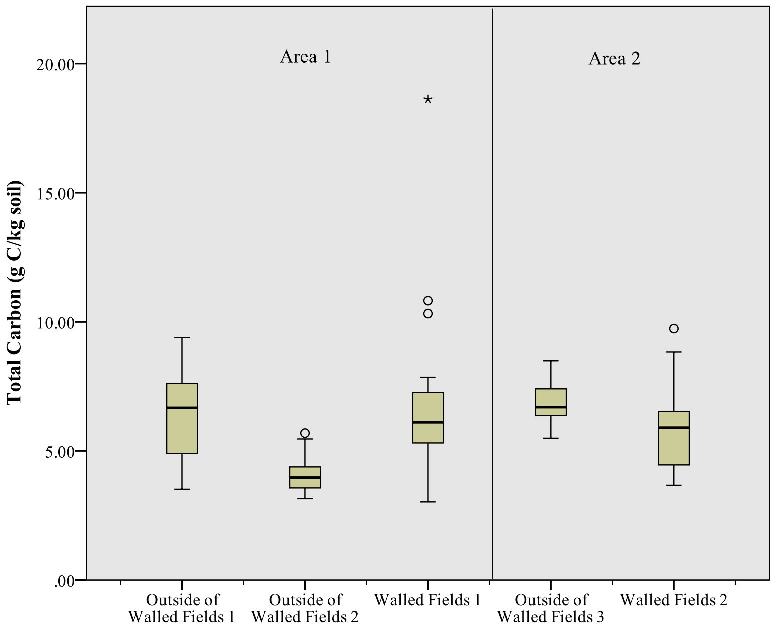


Figure 6.5l: Total Carbon. Total carbon is significantly higher in one unwalled field in Area 1 and the unwalled field in Area 2.

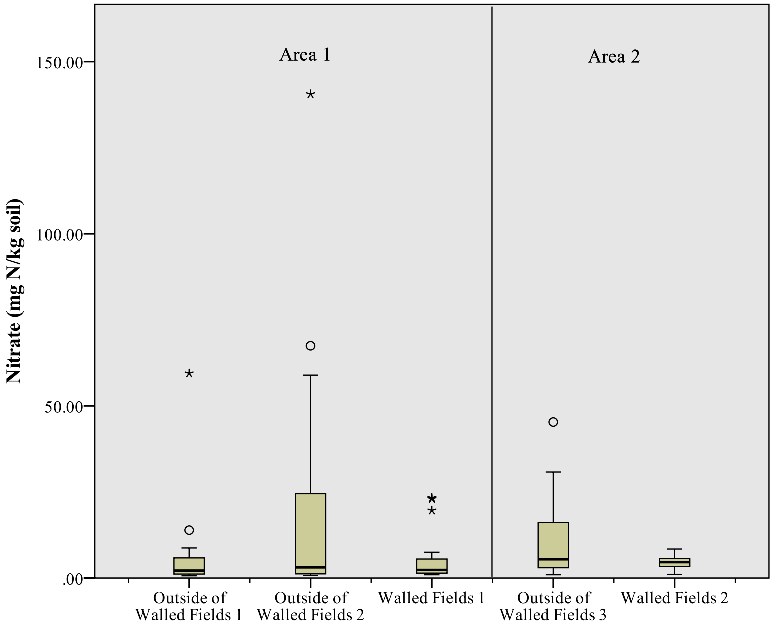


Figure 6.5m: Nitrate (Available Nitrogen). Nitrate is significantly higher in one unwalled field in Area 1 and the unwalled field in Area 2.

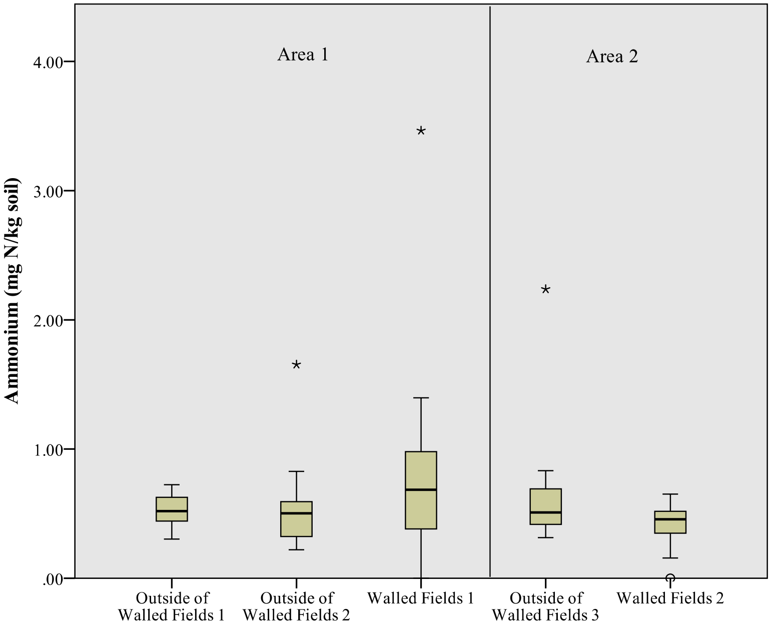


Figure 6.5n: Ammonium (Available Nitrogen). Ammonium is significantly higher in unwalled field in Area 2.

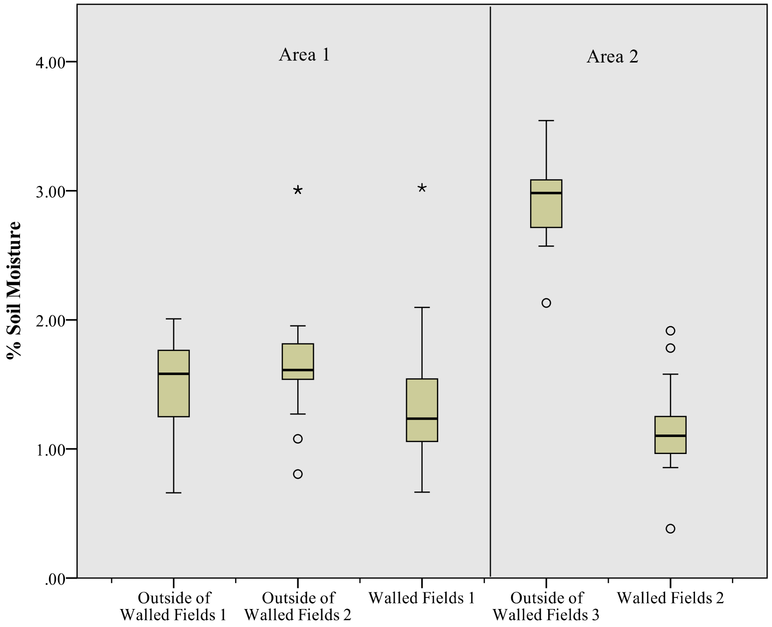


Figure 6.5o: % Soil Moisture. % Soil moisture is significantly higher in the unwalled field in Area 2.

Table 6.8: Statistical Differences between Walled Field Areas and Unwalled Areas in Area 1 (N= 20 for each field area)

		Significantly different?	Enhancement or Degradation	Mean	Std. Deviation	Sig.
Characteristics Essential for Successful Plant Cultivation						
% Clay	Walled Fields 1			11.3	2.2	.374
	Outside Walled Fields 1			10.4	2.2	
	Outside Walled Fields 2			10.4	2.3	
% Silt	Walled Fields 1	Higher in one unwalled field.	Degradation in walled field compared to one unwalled context	38.2	3.4	.000
	Outside Walled Fields 1			36.4	5.7	
	Outside Walled Fields 2 ***			42.4	3.8	
% Sand	Walled Fields 1	Lower in one unwalled field.	Degradation in walled field compared to one unwalled context	50.5	4.7	.004
	Outside Walled Fields 1			53.2	7.0	
	Outside Walled Fields 2 **			47.2	4.7	
% Coarse Fragments	Walled Fields 1 ***	Higher in walled field.	Degradation in walled field	23.0	9.4	.000
	Outside Walled Fields 1			12.0	2.9	
	Outside Walled Fields 2			8.8	6.1	
Organic Matter Loss on Ignition (%)	Walled Fields 1			2.32	0.66	.586
	Outside Walled Fields 1			2.20	0.31	
	Outside Walled Fields 2			2.19	0.25	

Total Nitrogen (g N/kg)	Walled Fields 1 **	Higher in walled field.	Enhancement in Walled field	0.72	0.28	.001
	Outside Walled Fields 1			0.54	0.09	
	Outside Walled Fields 2			0.51	0.08	
Electrical Conductivity (dS/m)	Walled Fields 1			6.5	4.1	.413
	Outside Walled Fields 1			6.9	3.3	
	Outside Walled Fields 2			8.2	5.4	
Sodium Adsorption Ratio	Walled Fields 1 *	Lower in walled field.	Enhancement in walled field	1.3	0.4	.036
	Outside Walled Fields 1			2.1	1.7	
	Outside Walled Fields 2			2.2	1.0	
Available Phosphorus (mg P/kg soil)	Walled Fields 1 ***	Higher in walled field.	Enhancement in walled field	10.5	4.2	.000
	Outside Walled Fields 1			6.6	2.5	
	Outside Walled Fields 2			6.6	3.3	
Characteristics Less Important for Successful Plant Cultivation						
Bulk Density (g/cm^3)	Walled Fields 1			1.46	0.11	.678
	Outside Walled Fields 1			1.47	0.07	
	Outside Walled Fields 2			1.48	0.06	
pH	Walled Fields 1	Lower in one unwalled field.	Degradation in walled field compared to one unwalled context	8.2	0.2	.000
	Outside Walled Fields 1			8.3	0.1	
	Outside Walled Fields 2 ***			7.9	0.2	
Total Carbon (g C/kg soil)	Walled Fields 1	Lower in one unwalled field.		6.8	3.3	.000
	Outside Walled Fields 1			6.3	1.6	
	Outside Walled Fields 2 ***			4.1	0.8	

Nitrate (mg N/kg soil)	Walled Fields 1	Higher in one unwalled field.	Degradation in walled field (mixed)	5.58	7.15	.050
	Outside Walled Fields 1			6.39	12.95	
	Outside Walled Fields 2 *			20.36	33.67	
Ammonium (mg N/kg soil)	Walled Fields 1			0.80	0.71	.090
	Outside Walled Fields 1			0.52	0.13	
	Outside Walled Fields 2			0.53	0.30	
% Soil Moisture	Walled Fields 1			1.36	0.51	.071
	Outside Walled Fields 1			1.49	0.37	
	Outside Walled Fields 2			1.70	0.51	

Note. Data are means and standard deviations for walled and unwalled sampling sites.
One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate different from other field contexts within the same geomorphic surface)

Table 6.9: Statistical Differences between Walled Field Areas and Unwalled Areas in Area 2 (N=20 for both field areas)

		Where significantly different?	Enhancement or Degradation	Mean	Std. Deviation	Sig.
Characteristics Essential for Successful Plant Cultivation						
% Clay	Outside Walled Fields 3 **	Lower in walled field.	Degradation in Walled field	12.9	4.0	.001
	Walled Fields 2			9.3	2.0	
% Silt	Outside Walled Fields 3 ***	Lower in walled field.	Degradation in Walled field	53.7	3.7	.000
	Walled Fields 2			29.9	4.9	
% Sand	Outside Walled Fields 3	Higher in walled field.	Degradation in Walled field	33.5	4.0	.000
	Walled Fields 2 ***			60.8	5.3	
% Coarse Fragments	Outside Walled Fields 3	Higher in walled field.	Degradation in Walled field	12.4	4.3	.000
	Walled Fields 2 **			21.8	4.8	
Organic Matter Loss on Ignition	Outside Walled Fields 3 ***	Lower in Walled Field	Degradation in Walled field	3.62	0.21	.000
	Walled Fields 2			1.79	0.22	
Total Nitrogen (g N/kg of soil)	Outside Walled Fields 3 **	Lower in walled field.	Degradation in Walled field	0.68	0.08	.001
	Walled Fields 2			0.53	0.16	
Electrical Conductivity (dS/m)	Outside Walled Fields 3			7.7	4.0	.213
	Walled Fields 2			6.4	2.1	

Sodium Adsorption Ratio	Outside Walled Fields 3 Walled Fields 2			1.6 1.2	0.6 0.6	.056
Available Phosphorus (mg P/kg of soil)	Outside Walled Fields 3 Walled Fields 2			11.7 11.4	5.5 5.0	.854
Characteristics Less Important for Successful Plant Cultivation						
Bulk Density (g/cm^3)	Outside Walled Fields 3 Walled Fields 2 ***	Higher in walled field	Degradation in Walled field	1.36 1.54	0.07 0.07	.000
pH	Outside Walled Fields 3 * Walled Fields 2	Lower in walled field.	Would not Significantly Affect Crop Production	8.2 8.1	0.2 0.2	.021
Total Carbon (g C/kg of soil)	Outside Walled Fields 3 * Walled Fields 2	Lower in walled field.	Degradation in Walled field	6.9 5.9	0.8 1.7	.029
Nitrate (mg N/kg of soil)	Outside Walled Fields 3 ** Walled Fields 2	Lower in walled field	Degradation in Walled field	10.53 4.51	11.51 2.14	.027
Ammonium (mg N/kg of soil)	Outside Walled Fields 3 ** Walled Fields 2	Lower in walled field.	Degradation in Walled field	0.62 0.41	0.41 0.16	.041
% Soil Moisture	Outside Walled Fields 3 *** Walled Fields 2	Lower in walled field.	Degradation in Walled field	2.91 1.14	0.30 0.35	.000

Note. Data are means and standard deviations between walled and unwalled sampling sites.

One-Way ANOVA Tests Were Run to Determine Statistical Differences.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (stars indicate different from other field contexts within the same geomorphic surface with stars on higher number

Assessing Research Theme 1 on the North Coast of Peru: The Longevity of Irrigation Systems and Soil Quality

In order to address how the longevity of irrigation affected soils on the Pampa, I provide results on a number of different groupings of the field systems at different scales. First, I compare soils from the ridges and the furrows to argue that by using ridges and furrows, salinity is controlled in irrigated fields across the Pampa and nutrients are added to where plants are being cultivated in the furrows. Second, overall total nitrogen throughout the Pampa presents a serious threat to the production of crops. I present evidence on the possible inputs that may have been used prehispanically and conclude that the most likely input would have been sedimentation from the application of irrigation water. Finally, I provide two contexts – the waffle garden fields and an anthropogenic deposit – to argue that sedimentation occurred, albeit in highly localized contexts, on the Pampa.

The Control of Salinity with Ridges and Furrows. Despite the overall moderate values of electrical conductivity and sodium adsorption ratio on the Pampa today (EC is approximately 7 dS/m and the SAR is approximately 1.5), the control samples collected as part of the agricultural field sampling done in 2002 (Nordt et al. 2004), show that natural soils were likely lower in salt prior to agricultural use (EC > 4.0 dS/m) (Noller 1993; Nordt et al. 2004). Importantly, because irrigation agriculture added moderate amounts of salt to the soils, prehispanic farmers would have needed to mediate the accumulation of salts in the soil.

The soil analysis from the ridges and furrows indicates that important nutrients are concentrating in the furrows, while salts and sodium are higher in the ridges. Research on sustainable agricultural techniques has shown that using ridges and furrows within agricultural fields allows for salts to accumulate at the top of the ridge through capillary action, thus diverting the salt away from the crops (Bernstein and Fireman 1957; Carter 1975). Additionally, sedimentation from irrigation water within the irrigation furrows increased important nutrients on these planting surfaces. It appears then, that using the ridges and furrows within agricultural fields, was an important strategy to prevent salt accumulation and concentrate nutrients on planting surfaces.

Combatting Overall Low Total Nitrogen in Pampa Soils. This analysis and previous analyses (Nordt et al. 2004) have confirmed that total nitrogen levels in the soil (on average 0.59 g N per kg of soil) and available phosphorus levels are far too low to cultivate maize in irrigated fields on the Pampa. Because crops were successfully cultivated for 600 years on the Pampa, this low level of nitrogen indicates that additions of nutrients prehispanically were needed to successfully produce a maize crop. Three potential sources of nutrients – camelid dung, seabird guano, and organic-rich sediments from irrigation water – may have been used as fertilizer in agricultural fields on the Pampa in the past in order to increase nitrogen levels in the soil.

Historic documents indicate that bat guano, rich in nitrogen available and on islands off the coast of Peru, was a major trade good during the historic period (Cushman 2008; Hollett 2008). Additionally, the use of camelid dung has been documented ethnographically in high altitude tuber cultivation (Franklin 1982). Little is known about their use prehispanically, but some have speculated that both guano and camelid dung could have been applied to fields as fertilizer to maintain agricultural productivity (Netherly 1977). For example, Sandor and Eash (1995) speculated that elevated levels of phosphorus in terraces in the Colca Valley may have been due to the application of guano prehispanically. Fortunately, methodological advances have been made to detect nitrogen isotopic signatures in plant and soils in an attempt to locate signatures of prehispanic fertilization (Bogaard et al. 2007; Fraser et al. 2011; Kanstrup et al. 2012; Szpak et al. 2012).

For this reason, twelve agricultural samples from the Pampa were tested for nitrogen isotopic signatures of these natural fertilizers, but none showed signs of guano or camelid dung use in soils (Szpak, personal communication). While these samples represent a pilot study of the use of prehispanic fertilizer across the entire Pampa, the lack of evidence for seabird or camelid guano use on the Pampa indicates that the addition of nutrients and sediments from irrigation water would have been a likely source to maintain production in agricultural fields.

Evidence for Sedimentation. Because inputs are needed in Pampa soils in order to maintain agricultural productivity, evidence for sedimentation is explored across the Pampa to understand if this process would have been occurring prehispanically. Two areas have shown evidence for the addition of fine sediments and nutrients on the Pampa – the waffle garden fields and a buried anthropogenic deposit.

The waffle garden fields are unlike any other fields on the Pampa and show interesting differences when compared to other fields across the Pampa. The soils in the waffle gardens have higher levels of silt, lower levels of coarse fragments, higher organic matter, higher total and available nitrogen, and higher total carbon. Statistically, they are not comparable due to different sample sizes, but this comparison shows that these differences should be observed further in future studies on the Pampa. The soil quality in the waffle garden field is clearly higher than that of other parts of the Pampa and indicates this field area may have received soil additions to improve the quality of soil for the production of agricultural crops (Table 6.10).

Table 6.10: Soil Results from Waffle Garden Fields Compared to the Rest of the Pampa Agricultural Fields

	All Field Samples Except From Waffle Gardens (n=207)		Field Samples from Waffle Gardens (n= 20)	
	Mean	Std. Deviation	Mean	Std. Deviation
Characteristics Essential for Successful Plant Cultivation				
% Clay	10.0	3.7	11.6	3.2
% Silt	35.1	9.7	46.7	3.4
% Sand	55.0	11.7	41.7	5.1
% Coarse Fragments	17.2	7.6	6.2	1.9
Available Phosphorus (mg P/kg soil)	11.7	6.6	12.1	5.5
Organic Matter Loss on Ignition (%)	2.17	0.78	2.94	0.66

Total Nitrogen (g N/kg soil)	0.58	0.19	0.64	0.26
Electrical Conductivity (ds/cm)	7.0	3.7	7.4	2.6
Sodium Adsorption Ratio	1.5	0.9	1.0	0.3
Characteristics Less Important for Successful Plant Cultivation				
Bulk Density (g/cm^3)	1.47	0.14	1.38	0.07
pH	8.1	0.2	8.2	0.1
Total Carbon (g C/kg soil)	5.84	2.25	6.27	3.01
Nitrate (mg N/kg soil)	7.7	14.6	10.1	8.3
Ammonium (mg N/kg soil)	.9	3.0	1.0	.7
% Soil Moisture	1.44	0.83	2.23	0.49

Figure 6.6: Waffle Garden Fields on the Pampa

In addition to the waffle garden fields, during geomorphic sampling in 2008 on the Pampa de Chaparrí, Huckleberry and others (2008, 2012) located a buried deposit that was clearly anthropogenic in origin, similar to the buried agricultural fields observed on the middle Gila River. While the original methodology for sampling on the Pampa did not involve the identification and sampling of buried anthropogenic deposits, two soil samples were collected to understand the soil composition of this anthropogenic deposit. Figure 6.7 shows one of the buried anthropogenic deposits, and Table 6.11 displays the descriptive statistics of the anthropogenic deposits compared to the surface field samples.

Figure 6.7: Buried Anthropogenic Deposit on the Pampa de Chaparrí

Table 6.11: Soil Characteristics of Anthropogenic Deposit and Surface Field Soils Compared

	Anthropogenic Deposit (N=2)		Surface Field Soils (N = 223)	
	Mean	Std. Deviation	Mean	Std. Deviation
Characteristics Essential for Successful Plant Cultivation				
% Clay	19.7	7.0	10.0	3.5
% Silt	46.2	20.8	36.1	9.8
% Sand	34.1	27.7	53.9	11.7
% Coarse Fragments	17.46	5.45	16.19	7.98
Organic Matter Loss on Ignition (%)	3.95	1.36	2.22	0.78
Total Nitrogen (g N/kg soil)	0.70	0.09	0.59	0.20
Electrical Conductivity (dS/m)	10.4	1.7	7.0	3.6
Sodium Adsorption Ratio	0.7	0.1	1.5	0.9
Available Phosphorus (mg P/kg soil)	10.0	4.2	11.7	6.5
Characteristics Less Important for Successful Plant Cultivation				
Bulk Density (g/cm^3)	N/A	N/A	1.46	0.14
pH	7.7	0.1	8.1	0.2
Total Carbon (g C/kg soil)	10.1	2.5	5.8	2.3
Nitrate (mg N/kg soil)	7.30	7.97	7.94	14.17
Ammonium (mg N/kg soil)	5.41	3.37	0.90	2.81
% Soil Moisture	5.87	1.89	1.47	0.72

As can be seen in the soil characteristics, the soil quality from the anthropogenic deposit is much higher than those from the surface fields sampled as a part of this dissertation. The anthropogenic deposit is higher in total carbon, total nitrogen, soil organic matter, and finer sediments (clays and silts). A comparative analysis of surface and buried field samples on the middle Gila River did show some significant differences in soil (e.g., electrical conductivity), but only what is expected with soil characteristics and increasing depth in the soil profile, since certain characteristics are driven by depth below surface (e.g., the movement of salts and clays down the soil profile over time). Thus, it appears that this anthropogenic deposit is higher in soil quality due to sedimentation and not because it is buried, unlike other fields on the surface of the Pampa. Like the buried agricultural deposits on the Middle Gila, sedimentation from irrigation waters added, at least in limited parts of the Pampa de Chaparrí, important nutrients and sediments to improve soil quality.

Evidence from both the waffle garden fields and the anthropogenic deposit indicates that sedimentation did occur, albeit in highly localized contexts, on the Pampa. It is unknown why most of the surface fields do not show evidence for sedimentation, although it is possible that sedimentation would have occurred within these fields prehispanically to increase nitrogen and other nutrients in the soil. It is likely that this is due to postabandonment processes. Most of the fields on the Pampa are located at the surface, and these surface fields are going to be more subject to deflational and erosional processes.

Assessing Research Theme 2 on the Pampa de Chaparrí: The Intensification of Agriculture and Soil Quality

In comparing two cases of unwalled and state-controlled walled fields, it appears that in both locations, walled fields have been subject to more degradation than adjacent, unwalled fields. In location 1, the walled field shows evidence for erosion (although whether this occurred during prehispanic agricultural use or post-abandonment is unclear). It is possible that intensive use prehispanically affected the post-abandonment growth of vegetation, leading to higher levels of erosion within the walled field in Area 1.

In the second walled field, soils are highly degraded with lower amounts of nutrients and fine sediments compared to an agricultural field outside a wall. Thus, unlike the middle Gila River, intensification on the Pampa led to degradation, either manifested in increased erosion or in decreased organic matter and essential nutrients. These conclusions represent important differences in the effects of the intensification of agriculture on soil quality among fields on both the middle Gila and north coast of Peru. Potential reasons for this departure are discussed in depth in the following chapter.

Chapter Summary

The analysis presented here provides a number of different theoretical and methodological contributions for understanding long-term soil quality management under intensive irrigated systems. Soil results from the Phoenix Basin and the north coast of Peru suggest that farmers in both regions were able to successfully manage soil quality for hundreds of years. On the middle Gila River, it appears that both long-term irrigation and the transition to a market economy and the resulting intensification of agriculture enhanced soils. A few key measures of soil fertility, including total nitrogen and organic carbon, are higher in the more intensively used historic fields, indicating that the addition of more irrigation water to the agricultural fields maintained and enhanced soil quality at this time. While irrigation added moderate amounts of salts to the soil, which ethnographic sources indicate were effectively managed historically (until the loss of water on the middle Gila River), fine sediments and nutrients are higher in irrigated fields compared to control samples. These conclusions indicate that the addition of sediments from the suspended load in the irrigation canals was a key strategy to maintain soil quality over the course of a millennium of cultivation.

On the Pampa de Chaparrí, however, more intensively used walled fields show signs of erosion and deflation, indicating that soils were more degraded and subject to erosion than their unwalled counterparts. Like the middle Gila, however, farmers created techniques in order to maintain soil quality over the long-term. On the Pampa, farmers constructed ridges and furrows to draw salts away from planting surfaces in the furrows through capillary action. Additionally, sedimentation is another important process that has been observed in localized areas across the Pampa that likely added nutrients and finer sediments to otherwise coarse soils that are low in total nitrogen. While not as widespread as on the middle Gila, sedimentation can be seen in localized contexts on the Pampa and within the furrows in the fields themselves.

The following chapter builds upon these soil results and assesses the extent to which irrigation was centrally managed and the effects of management on the sustainability and longevity of irrigation systems in these regions, including ancient irrigation in Mesopotamia and select modern regions.

Chapter 7

DISCUSSION ON THE ROLE OF IRRIGATION MANAGEMENT AND THE SUSTAINABILITY OF THE SYSTEM

The previous chapter addressed how soils were directly impacted by both the longevity and intensification of irrigation agriculture. Extensive literature on the sustainability and agronomy of modern irrigated agriculture indicates that the management of irrigation systems also may affect the long-term ecological sustainability of irrigated fields. Although the sampling design did not allow for the direct relationship to be explored with the data presented in previous chapters (e.g., Carr 2002; Dryzek 2005; Hickey and Mohan 2004), multiple ancient and modern case studies, including the Phoenix Basin, coastal Peru, and Mesopotamia, provide the opportunity to explore how the sustainability of the irrigation system may have been differentially affected by different management systems.

Sociopolitical organization governs the form of the management of irrigation systems, and irrigation can be managed at a number of different scales, from state-level administrators to the farmers themselves (e.g., Farrington 1977; Howard 2006; Lansing 1991; Netherly 1984; Wittfogel 1957; Woodson 2010). *How, then, does the extent to which the management of large-scale irrigation is centralized relate to the sustainability of the system?* In this section, I provide information from both ethnographic and archaeological case studies on how irrigation has been managed in ancient irrigation systems and is currently managed in modern irrigation systems. I then assess the tradeoffs of each management regime and evaluate how the case studies in the dissertation can inform hypotheses on the relationship between the centralization of management and the sustainability of irrigation agriculture. While the relationship between management and soil quality cannot be directly assessed empirically with the data collected for this dissertation, the importance of management in the sustainability of irrigation agriculture is clear and deserves thoughtful consideration.

Irrigation Management Strategies

Decisions concerning the management of irrigation water and agricultural fields have wide-ranging effects on the long-term sustainability, vulnerability, and overall success of the system to produce agricultural crops. Here, ***irrigation management*** is defined as the structure and centralization of decision-making concerning the distribution of water and agricultural strategies. These decisions can include what crops are grown within the field, when irrigation water is received, who needs to build and maintain canals, and how often fields are left fallow. Theoreticians have outlined two approaches to decision-making: top-down and bottom-up controlled management strategies, although many options for management exist in between (e.g., Erickson 2006; Ostrom et al. 1999; Smith 2008). Top-down management describes a system in which the agricultural decision-making was controlled by and centralized with elite leaders who have a vested interest in seeing surplus (and thus, tribute) created from the agricultural system. In an irrigated system controlled by bottom-up management, on the other hand, the farmers and the local community maintain control over the decisions concerning their agricultural fields, such as the distribution and timing of water or crop selection (Erickson 2006; Hunt 1988).

Because irrigation has occurred at a large scale (on the order of hundreds of thousands of hectares) both in the past and today and its success is highly dependent on the cooperation of hundreds of people, a debate has taken shape concerning whether bottom-up management was possible with large-scale irrigated agricultural systems (Erickson 2006; Janusek and Kolata 2004; Johnson and Earle 1987; Lansing 1991; Netting 1993; Treacy and Denevan 1994). While many researchers argue that large-scale systems, like those observed on the north coast of Peru, required top-down leadership from a centralized authority (Janusek and Kolata 2004; Johnson and Earle 1987; Kolata 1986), others maintain that bottom-up management of large-scale agricultural systems is not only possible but preferred for the sustainability of the system (Erickson 2006; Lansing 1991; Netting 1993; Treacy and Denevan 1994).

After Wittfogel published *Oriental Despotism* in 1957, the belief that large-scale irrigation systems required centralized authority for their management became ingrained in archaeological research for decades (Earle 1978, 1997; Kolata 1993; Janusek and Kolata 2004; Mencher 1966; Millon et al. 1962; Wheatley 1971). Archaeologists spent many years attempting to directly link the size of the irrigation system with the centralization of management, to document that the larger the system, the more centralized management was necessary for its success in resolving conflict and adequately producing a surplus of agricultural goods (e.g., Mencher 1966; Millon et al.

1962; Earle 1978). Thus, archaeologists came to assume that large-scale agricultural systems were directly controlled by centralized management systems.

Hunt (1988), however, criticized these studies, pointing to their low sample size and little evidence for the direct relationship between the size of the irrigation system and the extent to which management was centralized. He provided multiple examples of small-scale irrigation systems (700 hectares of irrigable land in Indonesia) controlled by the centralized authority of the state and large-scale systems managed by community-based charters (e.g., 458,000 hectares of irrigable land along the King's River in the United States), challenging the direct association between the centralization of management and the complexity of the irrigation system. Other researchers have also criticized the Wittfogel argument with numerous examples across the world of intensive, large-scale agriculture that functioned for centuries without centralized state sociopolitical organization (Denevan 2001; Doolittle 2000; Erickson 1992; Howard 2006; Lansing 1991; Lehmann 2003; Mabry and Cleveland 1996; Treacy and Denevan 1994).

The Relationship between the Sustainability and Management of Irrigation Systems

Chapter 1 highlighted the rapid expansion and intensification of new irrigated lands over the last few decades, emphasizing the need to fully understand the long-term ecological consequences of irrigation agriculture. The previous chapter presented important differences in soil quality in ancient fields in the Phoenix Basin and on the north coast of Peru and provided results on how soils are affected by both the longevity and intensification of irrigation agriculture. Many irrigated agricultural systems in the past and today, however, have been subject to serious environmental problems, like salinization and waterlogging. Why, then, do cases like the Phoenix Basin and coastal Peru experience some success in long-term irrigation agriculture, while others, like Mesopotamia, suffer massive collapses? The answer is likely not an ecological one, but lies in the organization used to distribute water and manage agricultural decision-making across an irrigation system. The role of irrigation management has taken a central place in understanding the sustainability of irrigation systems, due to the importance of irrigation management in when and how water is received, which can then in turn affect agricultural strategies, like flushing of fields or timing of agricultural fallow.

In the past, sustainability scientists argued that top-down management was the key in creating stable and sustainable irrigation systems (e.g., Carr 2002; Dryzek 2005; Hickey and Mohan 2004). Citing the importance of Western scientific knowledge in understanding how to successfully distribute water equitably among farmers, resolve conflicts over water distribution, and manage suspended salts and sediments, top-down management was heralded as the future in feeding the world’s population in the centuries to come (Carr 2002; Volger and Jordan 2003). Researchers in irrigation science, who were not farming the fields themselves, incorporated regular rotational water schedules, major infrastructural changes to the canals, and desalinization plants in irrigated systems across the world in order to maintain agricultural productivity, resulting in immense financial costs to national governments (Lansing 1991; Oster and Wichelns 2003; Smith 2008; van Schilfgaarde 1994; Wichelns and Oster 2006).

These top-down systems, however, have resulted in failure over the past decades, both in the maintenance of agricultural productivity and in the equitable distribution of water to farmers, resulting in criticism of this approach (Agrawal and Gibson 2001; Smith 2008). Numerous instances of irrigation failure in many modern cases, as seen in state-managed systems in the United States, Pakistan, and China, have been cited as failures to create a sustainable large-scale irrigation system with top-down, centralized management (Brownell and Eaton 1975; Gardner and Young 1988; Hundley 2009; Lohmar et al. 2003; Meyers 1966; van Schilfgaarde 1994; Wichelns and Oster 2006; Xie et al. 2011). These systems, however, operate on a much larger scale than the ancient contexts discussed in this dissertation and in addition to providing water for agricultural purposes, they need to provide water for municipal use and the production of hydroelectricity.

For example, federal and state governments centrally manage the Colorado River, which now waters the Phoenix Basin, including the Gila River Indian Community. The Colorado River has become a case study of mismanaged water distribution and salinized fields (Glenn et al. 1996; Johnson and Haight 1984; Ward 2003). Wichelns and Oster (2006) point to the Colorado River as a prime example of how centralized solutions to ecological degradation and water shortages lead to costly and frequently unsuccessful solutions. For example, a tenet of the 1944 treaty between Mexico and the United States concerning the Colorado River water stated that the water salinity needed to meet specific standards when the river reached Mexico, resulting in the need for the United States to improve water quality in the Colorado River (Leitz and Ewoldsen 1978). Several technological options were available to decrease the amount of suspended salts in the Colorado River water, including increasing the efficiency of irrigation upstream, which could have decreased salt loads at a relatively low cost (van Schilfgaarde 1982). This solution, however, would have involved intensive collaboration and agreements with individual farmers to improve farm-level use of irrigation water. The United States government, instead, decided to construct a desalting plant at a huge financial cost of $250 million, and this plant is currently not functioning due to infrastructural problems. Salinity levels of the water, not surprisingly, remain high. Wichelns and Oster (2006) highlight this failure as a direct result of top-down management policies, instead of communicating with farmers and allowing them to increase irrigation efficiency and improve water quality.

With these failures in top-down management in adequately distributing water and preventing environmental problems and the realization that large-scale systems do not need centralized management to succeed (e.g., Erickson 2006; Hunt 1988), sustainability scientists argue for the benefits of bottom-up management, in which control over decision-making of water allocation and farm management lies in the hands of the farmers and their communities (Bjornlund 2010; Mabry and Cleveland 1996; Ostrom 1993, 1999; Weissing and Ostrom 1991). Numerous ethnographic studies of smaller scale systems that more accurately reflect those analyzed in this dissertation support the assertions made by sustainability scientists concerning the promise of bottom-up management of these complex agricultural systems. Modern examples from Peru and Bali have long-lived irrigation systems that are managed at the community level, have maintained agricultural production, and equitably distribute water to farmers within the irrigation systems (Erickson 2006; Gelles 1994; Lansing 1987, 1991, 2006).

Trawick (2001) provides a modern example from Peru in which he outlines the decentralized, complex agreements that Peruvian farmers have in which incentives are provided to follow the rules and equity and transparency are highlights of the system. In this system, if someone is caught taking more water than their allocation, or "cheating the system," they are penalized allocation of water the next day, creating an immediate and noticeable consequence. Because the system is managed by the farmers, who are aware through frequent community meetings on the timing and distribution of water, the cheaters, although scarce in this system due to the incentives for appropriate water allocation, are frequently caught and punished.

Ethnographic research by Lansing (1991) in Bali further establishes the benefits of bottom-up management and the destructive effects of transitioning to centralized management in an irrigated system. For hundreds of years, farmers in Bali created a complex, community-based agricultural strategy of managing their agroecosystem and water rights. In this complex religiously based system, priests of the water temples managed strict watering schedules, and farmers incorporated hundreds of years of knowledge concerning cropping that had beneficial biological feedbacks to keep the system in equilibrium. These systems functioned sustainably and productively from the 12th century AD until the 1970s and 1980s when Balinese authorities attempted to control the irrigation system from the top down in order to introduce policies of the Green Revolution to increase agricultural production. With the takeover by state-controlled interests, decision-making was removed from the hands of the farmers, and equilibrium of the system was lost, resulting in disastrous consequences for the ecological health of the system. From Lansing's and others' work, it is clear that bottom-up strategies of multi-village systems are possible for the successful integration of irrigated systems and are, in fact, preferable for the ecological sustainability of an irrigated system.

Smith (2008), however, highlights the serious drawbacks of bottom-up management of large-scale agricultural systems. She points to four limitations of the bottom-up approach – the resistance of government officials to fully trust the community to manage water resources, the myth of the "community" as a coherent group, the lack of resources of a small community to manage water resources, and the lack of knowledge of community members of how to incorporate water management – that can severely inhibit the management of a large-scale agricultural system at the community level. Smith cautions that managing these large-scale systems at the community level is extremely complex and takes a great deal of communication, compromise, and knowledge, all of which may not be available to farmers across the irrigation system. Additionally, financially poor communities may have an agreement in place to manage collective resources, but the funds may not be available to ensure that these plans are incorporated and followed on a large-scale.

While it appears that those irrigation systems that are managed from the community-level are more long-lived, little ecological data have been collected to understand how the different aspects of the irrigated agricultural ecosystem may be affected. While modern systems have shown signs of serious degradation under centralized management, they feed water to millions of hectares of agricultural fields and tens of millions of people. The FAO has done little research, however, on those irrigated lands that operate at a smaller scale, including those operating at hundreds of thousands of hectares (as compared to the those systems over a million hectares), like the north coast of Peru or Bali. Not surprisingly, archaeological examples can provide some insight into how to create a long-term sustainable irrigated agricultural system. Sustainability literature, however, infrequently cites archaeological research past the introduction of their scientific articles, which provide cautionary tales of failure and collapse from Mesopotamia, and then fail to draw extensively on the archaeological research of irrigation management. Archaeologists, though, have rigorously analyzed how irrigation was managed in many different irrigated systems across the world, including the Phoenix Basin (e.g., Abbott 2003), coastal Peru (e.g., Hayashida 2006; Netherly 1988), and Mesopotamia (e.g., Hruška 1995; Steinkeller 1987).

From these studies of the relationship between the longevity of irrigated systems and the centralization of management, the tradeoffs between top-down and bottom-up management of large-scale irrigation systems are clear. Large-scale systems are extremely hard to manage at the community level due to the large size and the number of people involved, but the bottom-up approach highlights the importance of traditional ecological knowledge (TEK) in incorporating effective strategies that maintain agricultural production over the long-term (Chambers and Gillespie 2000). These examples show that when farmers control decision-making over their agricultural fields, they can implement more sustainable strategies, which have been learned from their long-term experience with the agricultural system (Chambers and Gillespie 2000; Erickson 2006; Smith 2008). Local populations, however, may have difficulties incorporating this knowledge if a cohesive community cannot be formed or funds are not secured to implement plans to manage collective resources. The case studies in this dissertation can clarify the relationship between the centralization of irrigation management and the sustainability of the irrigated systems.

The Management of Ancient Irrigated Agricultural Systems

Archaeological case studies can refine our understanding of the longevity of irrigated systems. For decades, the theory that salinization brought down civilizations in Mesopotamia has had a foothold in archaeological lore, but has been little tested with ecological data (Artzy and Hillel 1988; Gibson 1974; Jacobsen and Adams 1958). While soils evidence is scant for evaluating salinization in ancient irrigated fields in the past, historic documents do indicate increasing problems of productivity due to salinization and sedimentation in Mesopotamia. In fact, Mesopotamia has become the default case study for how large-scale, state-level societies can collapse due to the environmental degradation from mismanaged irrigation systems (Krech 1999; Redman et al. 2009). Why, then, were the Hohokam and O’odham on the middle Gila and farmers on the north coast of Peru successful for millennia at controlling salt accumulation in their fields while agricultural systems in Mesopotamia and across the world today show evidence for repeated intervals of collapse (or, seriously decreased agricultural production) due to soil degradation? The following sections provide information on how irrigation was managed and explore how the management of the irrigation systems may be related to the sustainability of these case studies.

The Middle Gila River

Archaeologists have written many pages concerning the nature of management of the prehistoric Hohokam irrigation system, collecting large amounts of archaeological evidence to discern the management of the irrigation system. Estimates on the irrigable area are placed at 20,000 hectares of irrigated acreage along both the Salt and Gila Rivers to feed 10 to 20,000 people (Hunt et al. 2005). Abbott (2000) provides evidence of ceramic exchange throughout the Sedentary Period that supports the existence of individual canal system networks. The exchange of pottery implies important social ties that may reflect the social scale of Hohokam irrigation management. Focusing mainly on Canal System 2, Abbott finds that most ceramics moved *within* the canal system but not *across* to other canal systems. Abbott argues that this ceramic evidence indicates that irrigation was likely managed at the level of the individual canal system and the exchange of ceramics served to reinforce cooperation over water resources (Abbott 2000).

Hunt and colleagues (2005) further support this assessment by drawing upon a vast body of ethnographic research on the management of irrigation systems to evaluate the level at which the Hohokam irrigation system was likely managed. Their data indicate that any system larger than 1,000 hectares (and individual Hohokam canal systems commanded areas larger than thousands of hectares, depending on the estimate, see Hunt et al. 2005 for a discussion) required some form of organized management by the state, community, or private organization. They conclude, based on ethnographic cases that are structured similarly to the Hohokam, that their irrigation system was based at the community level.

The debate continues, however, regarding the management of the canals during the Classic Period, which may have become more centralized in the hands of leaders. While the Sedentary period Hohokam had a system based on exchange and kin relationships, hypotheses concerning the increasing centralization of irrigation management have been advanced for the Classic period Hohokam, during which over 40 platform mounds were constructed at regular intervals (~ 5 km) along irrigation canals throughout the Salt and Gila River basins after the ubiquitous ballcourts of the Sedentary period were abandoned (Doyel 1981; Fish 1996; Wilcox 1991). Some archaeologists argue that these platform mounds represent the amassing of power by elites by controlling labor and irrigation networks (Teague 1984; Wilcox 1987, 1991) and some interpret a hierarchy of site types, the largest of which exerted the most control over irrigation canals (Fish 1996; Howard 1987, 1993). This evidence, they contend, indicates that irrigation canals then may have been managed above the individual canal system and perhaps at the scale of the entire Salt and Gila Rivers. Others argue vigorously against this claim and assert that the irrigation networks never were managed *successfully* above the level of the canal system due to a lack of data for a centralized authority to manage an entire irrigation system (Abbott 2000, 2003; Gregory 1991). From these data, most agree that the entire irrigation system of the Salt and Gila Rivers was never managed as a whole; rather, management resided at the level of each single canal system, which fed 1,800 to 7,600 hectares of agricultural fields each (Abbott 2000; Abbott 2003; Gregory 1991; Howard 2006; Hunt et al. 2005; Woodson 2010; although see Masse 1981 and Howard 1993 for arguments to the contrary).

Even if management never became so centralized to the extent that one leader or group of elites controlled the water from the entire river, major changes in management of the prehistoric irrigation system of the Hohokam are evident with the onset of the Classic Period in AD 1150 and show increasing centralization over the Sedentary Period. For example, in his dissertation, Woodson (2010) argues that the prehistoric Snaketown canal system completely reorganized during this time. Woodson hypotheses that this reorganization could be due to a number of factors that would have affected how water can be distributed, including greater fluctuations in streamflow and the salinization of agricultural fields. If streamflow did indeed become a problem during the Classic Period, it is possible that the Hohokam's management strategies that led to successful use of the fields during the Preclassic Periods, such as the frequently flushing of the soils, could no longer be incorporated without a reliable source of water from the Gila River and with the reorganization of canals during the Classic Period.

Even under the intensification of agriculture during the historic period, farmers in the Phoenix Basin successfully maintained agricultural production and improved certain characteristics of the soil with very little evidence for salinization. Their farms only met failure when incoming Anglo farmers drew water off the river in the late AD 1800s, restricting their ability to incorporate strategies like sedimentation and flushing of salts that kept their system sustainable in the previous centuries. Historical evidence shows that the O'odham managed their water at the canal system level, in which people along the main canal drawing off the river formed an agreement on the distribution of water (Abbott 2000). It also appears that individual households maintained control over the decision-making concerning how crops were watered and grown within their fields (Henderson and Clark 2004; Howard 2006). This Preclassic strategy appears to have been much more successful than the later, more hierarchical strategies of the Classic Period, during which the Hohokam irrigation system disintegrated and the region was abandoned.

The Pampa de Chaparrí

Farmers on the north coast of Peru created similar success in their agricultural fields for hundreds of years, except perhaps in centrally managed state-controlled walled fields, one of which shows some evidence of degradation. Unlike the Phoenix Basin, however, irrigation systems along the north coast of Peru were likely under partial management of the state. Major canal systems, like the intervalley canals leading from the Moche Valley, were large-scale constructions in which state-level authorities had a significant hand in organizing labor to construct. While there is little evidence for a single ruler dictating and organizing the irrigation system in Peru, Netherly (1984) provides evidence for a dual nested hierarchy in which lords had control over irrigation systems in two different hierarchies. These hierarchies worked together to manage the irrigation systems on the north coast of Peru. Hayashida (2006) further demonstrates that during the Chimú and Inkan Empires, state level administrative buildings were built at important parts of the irrigation systems, likely indicating state officials exerted control over the management of irrigation on the Pampa at this time.

While the Pampa only irrigated 5,600 hectares of land, it was located with the larger context of the Chimú Empire. The Pampa is located within the Lambayeque region, which is comprised of 5 separate river valleys and fed 96,700 hectares of cultivable land for an estimated 123,000 people prehispanically. This irrigated acreage of the Lambayeque region has been estimated to represent one third of the irrigable acreage ***for the entire coast of Peru***, indicating its importance for agricultural productivity (Kosok 1965). The Lambayeque region, however, represents only the northern portion of the Chimú Empire, and estimates for irrigated acreage and population for the rest of the Chimú Empire are difficult to find. Population estimates place 20,000 – 40,000 people in the Chimú capital of Chan Chan alone and rural populations likely reached in the hundreds of thousands, as they did in the Lambayeque region (Moseley and Day 1988). Thus, while the Chimú Empire likely managed hundreds of thousands of irrigated acreage, this number still falls within the range of those systems found ethnographically by Hunt (1988) that were managed at the community level.

Unfortunately, archaeological evidence concerning irrigation management is limited and restricted to a few major sites, like the Chimú capital of Chan Chan. Because of the difficulty in reconstructing prehispanic irrigation management archaeologically, many of our interpretations concerning prehispanic management of irrigation agriculture come from early Spanish documents. Netherly (Netherly 1977, 1984, 1990)extensively analyzed Spanish documentation of early historic canal systems and found evidence for segmentary control, in which a dual nested hierarchy, largely decentralized from the state, managed these early historic irrigation systems**.** In this system, paramount lords ruled coastal valleys with a nested hierarchy of sociopolitical divisions drawn along canal branch lines (likely reflecting management by canal system similar to, although more complex than, the Hohokam in the Phoenix Basin). These documents also show a lack of administrative centers along canal systems and a lack of correspondence between site hierarchy and canal hierarchy also reinforcing the evidence that canals during the early historic period were not managed centrally by the state. While centralized management by the state did not exist historically, the distribution of and access to water was certainly not equal. The same documents indicate that, despite the uncentralized management at this time, land rights were held by elites who “loaned” the land out to agriculturalists for labor and loyalty to the state (Hayashida 2006; Ramirez 1996).

Because of the lack of archaeological data to infer prehispanic canal management, these Spanish documents represent our best evidence to understand the extent to which agricultural was controlled by the state (Hayashida 2006). Interpretation of prehispanic irrigation management from historic sources can be dubious, however, due to the slow influx of Spanish settlers into the region and the destruction of complex indigenous political systems needed to manage irrigation systems. These factors likely would have restricted the ability of the Spanish to observe any complex indigenous systems that may have fallen apart during the Spanish Conquest. Thus, while historic documents indicate an uncentralized management system of irrigation canals throughout the north coast of Peru, archaeologists have begun to doubt the extent to which these historic documents are truly reflective of prehispanic canal management.

To address this gap in our knowledge of prehispanic irrigation management, archaeologists have begun to analyze the relationship between settlement patterns and canals to understand how elites may have exerted control over the irrigation system (e.g., (Farrington 1977; Hayashida 2006; Keatinge 1974; Keatinge and Day 1973; Keatinge and Conrad 1983; Mackey and Klymyshyn 1990; Ortloff et al. 1982; Ortloff 1993; Pozorski 1987). They have found that the extent to which irrigation management was centralized changed during late prehistory on the north coast of Peru. During the Sicán Period, little archaeological research concerning irrigation management has been done, but limited archaeological evidence of the focus of Sicán elites indicates that irrigation systems were likely under segmentary control, as described in early Spanish historic documents (Netherly 1984; Hayashida 2006). Sicán leaders at this time were mostly focused on expanding religious power and trade networks, and the state had little interest in managing agricultural lands apart from exacting tribute from farmers (Shimada 2000).

Irrigation management changed significantly with the shift from Sicán to Chimú control of the north coast. Much of the archaeological research concerning the management of irrigation systems under Chimú control has been focused at Chan Chan, the capital of the Chimú Empire (Farrington 1977; Hayashida 2006; Mackey 1987; Moseley and Deeds 1982; Ortloff et al. 1985; Ortloff 1993; Pozorski 1987; Pozorski and Pozorski 2009). Archaeological evidence for Chimú control over agriculture and irrigation is clear. With the emergence of the Chimú Empire on the north coast, control of the irrigation system transferred to elite leadership as evidenced by the construction of *audiencias* near canal intakes (Keatinge 1974; Keatinge and Conrad 1983; Keatinge and Day 1973). These *audiencias*, which are rural administrative centers for elite households and centralized storage facilities, likely housed state administrators who exerted control over the construction and maintenance of the irrigation system and crop production (Keatinge 1974; Keatinge and Conrad 1983; Keatinge and Day 1973; Mackey 1987; Pozorski 1987). Additionally, agriculture fields closest to the capital are highly regular and orderly, indicating clear direction and control by higher forces to construct these fields (Farrington 1977).

To determine the extent to which elite leaders may have exerted control over irrigation canals, Mackey (1987) analyzed architectural characteristics of Chimú administrative centers across the north coast of Peru and their relationship to canal systems. She corroborated the presence of niched patios (used for redistributive ceremonies), *audiencias*, storeroom complexes, and burial platforms and discovered a ranked system of the administrative control across different regions along the north coast. The Chimú capital of Chan Chan controlled the production of crops by dictating the amount of goods accumulated by these secondary and tertiary administrative centers across the north coast. She argues, "… Chan Chan held the monopoly of elite goods, and, in the case of Machan [a secondary center], regulated the kinds of goods which could be produced" (1987: 128). Because leaders in Chan Chan needed to support specialized artisans and a hierarchy of administrative sites within its borders, leaders demanded huge surpluses in the form of tribute and exacted this tribute through force, if necessary. This surplus was demanded by the rural administrative centers scattered throughout its empire, with the control of irrigation systems and the distribution of water (Mackey 1987).

With the conquering of the Chimú Empire, the Inka quickly took control of coastal valleys and the Andes. Because the Inka Empire was so briefly in power prehispanically (less than 100 years), however, most of what we know about the management of their agricultural system is through Spanish documentation of their political processes. These historic documents, however, reflect an indigenous population that has been decimated by disease and warfare, and likely does not reflect prehispanic

Inkan management. Thus, the prehispanic Inka are frequently lumped with the Chimú archaeologically, since similarities exist between their regimes (Shimada 2000).

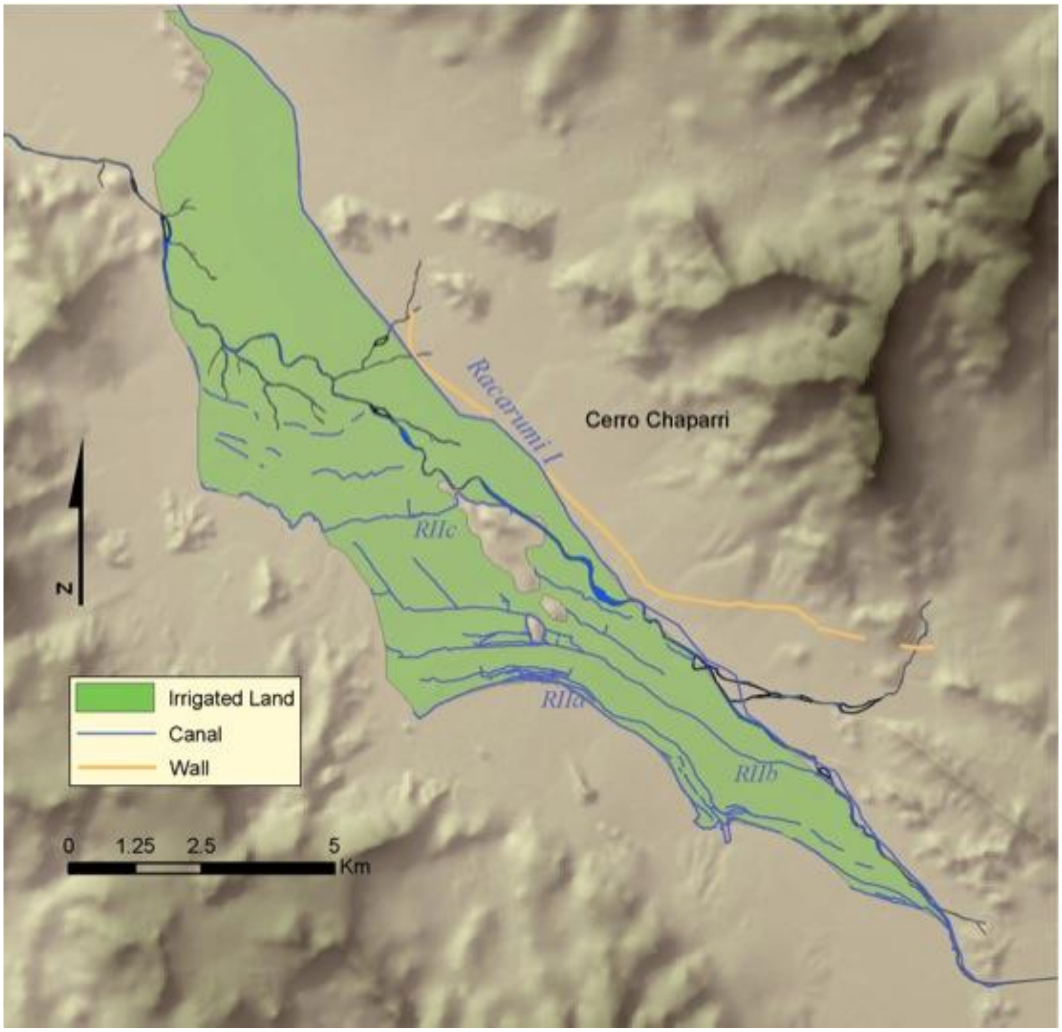


Figure 7.1: Irrigable Area and Major Canals on the Pampa de Chaparrí

The Proyecto Ynalche, directed by Dr. Frances Hayashida, has undertaken extensive archaeological survey across the Pampa to map archaeological sites, irrigation canals, and agricultural fields (Figure 7.1; Hayashida 2006). With these extensive surveys, Hayashida (2006) tests the hypothesis derived from early Spanish documentation that prehispanic irrigation systems were not centrally managed. During the middle and late Sicán period, large residential site clusters were located centrally and at intervals of 1.4 – 2.3 km apart along the main distributory canals in use at that time – the Racarumi IIA and IIC. Hayashida (2006) argues that this association indicates that sociopolitical divisions were likely drawn along the canal system, reflecting the segmentary control described in the early Spanish historic documents described above (Netherly 1984). Interestingly, the archaeological data also indicate stability in architectural and canal patterns throughout the middle and late Sicán periods, despite the political turmoil at the Sicán capital during this time.

Settlement patterns changed radically during the Chimú/Inka period. The number of sites exploded, indicating a rapid influx of new settlers with Chimú conquest of the Pampa. Many Sicán sites were abandoned, along with the RIIA distributory canal. Additionally, instead of clusters of residential sites located centrally along the canal systems during the Sicán period, residential sites were individually distributed along canals, indicating a breakdown of the sociopolitical divisions related to canal systems of the Sicán period. Administrative centers were also constructed at this time, the largest of which was built on top of Cerro Arena, centrally located at a high point on the Pampa where irrigation canals and newly built roadways could be observed (Hayashida 2006).

With her extensive archaeological data on the relationship between settlement patterns and the canal systems, Hayashida (2006) argues that under Sicán rule, irrigation management was largely decentralized from state administration and stable for over 475 years. Irrigation management then changed under Chimú and Inka rule. Highly visible administrative sites were constructed near headgates, and roadways appeared at this time to monitor the distribution of water and goods within and leaving the Pampa. Walled fields (see below) also appeared during the Chimú period, indicating another way in which the state exerted control over agriculture (Kolata 1990; Téllez and Hayashida 2004). This reorganization under the Chimú Empire led to major changes in domestic architecture, demonstrating that farmers were greatly affected by this new regime.

Evidence from both the Pampa and the larger north coast of Peru indicates that, like the prehistoric Hohokam, irrigation management changes through time from largely managed by farmers under a larger uninvolved Sicán state to becoming more concentrated into the hands of elites during the Chimú and Inkan Empires. Unlike the Hohokam, however, irrigation systems on the north coast, including those on the Pampa, were highly regulated and controlled by Chimú leaders and administrators.

Southern Mesopotamia

Mesopotamian irrigation systems are well known for their highly centralized management by state-level systems during certain points in its history – namely the Third Dynasty of Ur (2112 – 2004 BC) and the Sassanian Period (AD 224 - 681), both of which suffered devastating collapses (Adams 1978). The collapses of these major dynasties have been attributed to failure of the irrigation network, due to waterlogging or salinization (Adams 1966, 1978; Hruška 1995; Potts 1997; Renger 1995). Like the modern examples of irrigation failure, however, the Mesopotamian case has very little ecological data to support assertions of what actually led to its failure. Some soil evidence shows excessive sedimentation from irrigation canals, while historic documents indicate that leaders and bureaucrats were forced to change cropping patterns from wheat the barley to combat salinization (Artzy and Hillel 1988; Jacobsen and Adams 1958).

The availability of water in Mesopotamia is so important that archaeologists have focused on the interrelationship between the development of irrigation systems and political power (Hruška 1995; Potts 1997; Renger 1995; Weiss et al. 1993; Yoffee 1995). Not surprisingly, then, the mismanagement of the Mesopotamian irrigation system has been extensively linked to the collapse of cities and civilizations (Artzy and Hillel 1988; Gibson 1974; Jacobsen and Adams 1958). Population and irrigated acreage estimates are difficult to find for different points in Mesopotamian history (and this number would have varied through time), but the population of Ur, an important city state of the Sumerian Empire during the Ur III dynasty, has been estimated to be 65,000 people with hundreds of thousands more people living in other cities and outlying rural areas (Adams 1965). Estimated irrigated acreage has been published for the Lower Diyala Basin, a section of southern Mesopotamia, at 300,000 hectares (Mitchell 1959), so irrigated acreage for all of southern Mesopotamia likely approached over a million hectares, dwarfing the numbers irrigated by the Hohokam and Chimú.

Extensive historic documents from Akkadian and Sumerian sources record the massive control which the Ur III state had over many aspects of economic life in southern

Mesopotamia, including the management of irrigation water (Steinkeller 1987). Archaeologists have used these documents to argue that the distribution of irrigation water and construction and maintenance of canal systems were highly controlled by a centralized state bureaucracy (Hruška 1995; Yoffee 1995). These administrative documents show the partitioning and scheduling of labor to open headgates, clean out canals, or repair dams along the Tigris and Euphrates Rivers (Renger 1995). Because it appears that the state is organizing these activities in these documents, archaeologists have become convinced that a centralized authority managed irrigation agriculture at this time (although, see Rost 2011 for an interesting counterpoint).

Additionally, large-scale archaeological surveys undertaken by Adams in the 1960s and 1970s mapped extensive irrigation systems and their relationship to archaeological sites (Adams 1966, 1981). Adams (Adams 1978) argues that the highly regular gridlike patterning of irrigation systems during the Sassanian Period is a clear indicator that these canals were constructed by state-level administration that directed the development of these irrigation systems. Interestingly, these times of highly centralized irrigation management are those that have been cited to have major problems with waterlogging and salinization (Artzy and Hillel 1988; Gibson 1974; Jacobsen and Adams 1958). In addition, historic documents clearly indicate the involvement of the state in agricultural production with their descriptions of agricultural yields, seeding patterns, and labor schedules of farmers. While clear archaeological and ecological data are scant concerning the failure of the irrigation system, we do know that the success of these large, politically complex systems in southern Mesopotamia was tightly tied to the successful maintenance of irrigated agricultural production.

The environment of southern Mesopotamia, however, is highly susceptible to salinization. Soils high in fine sediments and a naturally high water table in the region allow for salts to readily accumulate in the soil both in the past and today, and experts agree that fallowing is the best way to control accumulating salts by decreasing the water table in between harvests (Artzy and Hillel 1988; Dileman et al. 1977; Hardan 1971). Interestingly, Pre-Sargonic texts (historic documents written *before* the creation and collapse of the Ur III civilization) cite agricultural practices known to prevent salinization and waterlogging in fields, including fallowing and leaching of fields (Powell and Kalb 1985). Thus, technological and ecological strategies were known and yet not employed before the ecological degradation of fields during the Ur III period. Why, then, did farmers during the Ur III and Sassanian Periods not incorporate known techniques to prevent these problems in their fields? Because the problems of soil degradation occurred under the most centralized management systems, archaeologists have linked the two together with little ecological data (Gibson 1974). Highly centralized management may have been involved in the inability to incorporate agricultural strategies used in the past, but this hypothesis needs to be tested further with direct soils data.

Modern Case Studies and Their Lessons on the Relationship Between Sustainability and the Centralization of Management

From the above archaeological case studies, the correlation between irrigation management and sustainability of the irrigation system begins to become clearer. In all cases, technological and ecological strategies were known to the farmers on how to prevent problems within the irrigation systems. Only in some cases, like the Phoenix Basin and unwalled fields on the Pampa de Chaparrí, were these strategies successfully implemented to maintain productivity over the long-term, and those cases were managed at the community or canal-system level. Farmers in the Phoenix Basin and coastal Peru used these strategies, including sedimentation, leaching of salts from fields, and the use of ridges to draw salts from planting surfaces. Centrally managed walled fields in Peru, however, show signs of serious degradation, and the highly complex Mesopotamian irrigation system resulted in collapse during the Ur III and Sassanian Periods. Additionally, as irrigation management became more centralized during the Classic Period in the Phoenix Basin, irrigation failed over time and resulted in the depopulation of the region. It is unclear, however, whether centralized management is directly linked to these failures or that other factors may be leading to soil degradation.

This correlation provides a hypothesis to test with future studies of soils in irrigation systems. If fields managed during time periods of different management regimes (e.g., Sedentary vs. Classic Period Hohokam, Sicán vs. Chimú States on the north Coast of Peru, or pre-Sargonic Period vs. the Ur III Dynasty in southern Mesopotamia) can be identified and sampled, the hypothesis concerning the salinization of fields and the centralization of management can be directly tested and evaluated.

Without direct soils data, though, ethnographic data may provide some insight into why bottom-up strategies seem to function more sustainably over time. These cases indicate that two potential answers – the importance of local ecological knowledge of the agroecosystem and the face-to-face interactions among members of the community – may allow for the creation of rules that effectively work for the ecological and social structure of the irrigated agroecosystem (Ostrom and Gardner 1993).

Perhaps most importantly to the irrigation system is the ecological knowledge, which is highly dependent on local environmental conditions, to properly maintain agricultural production. In a top-down system, decisions regarding schedules for when to receive water or when to fallow fields are typically made by high-level officials who are not involved in the farms themselves. The top-down process, then, removes the decision-making concerning agricultural strategies from the farmers and places it of the hands of public officials who know little about the specifics of farm management, fallow schedules, water needs, crop production, and other agricultural strategies for the local field conditions. As van Schillaffgaarde (1994: 207) points out, “the view from the top may be very different from the view at the bottom.” Multiple ethnographic case studies from Nepal (Ostrom and Gardner 1992), Peru (Trawick 2001), and Bali (Lansing 1991, 2006) have made it clear that an intimate knowledge of the agricultural system and its needs is essential to maintaining production over the long-term.

The most auspicious case illustrating the importance of local ecological knowledge of the agroecosystem is that of Bali. Lansing (1987, 1991, 2006) has extensively documented the agricultural system managed by the Balinese water temples and has observed its transition to a more centrally managed system in a takeover by the Balinese government. Before government takeover, the irrigators of this system created a complex system of rules, regulated by their religious system, which was highly in tune with their agroecosystem. The rules of the irrigation system were deeply embedded in the religious ideology of the irrigation users and dictated cropping patterns and allocation of water. These decisions, made by the water temples placed at regular intervals along the canal system, allow for a complex agroecosystem to function, including the control of insect pests through waterfowl and amphibians and the maintenance of soil quality through intercropping and crop rotation. This system was thrown into upheaval, however, when the state came in and tried to institute continuous rice cropping and ignored the institutions controlled by the water temples. This change led to collapse of the agroecosystem and loss of productivity in the irrigated systems, resulting in the state relegating control back to the water temples after a few decades (Lansing 1991).

The Bali case also highlights the importance of regular face-to-face interaction and the set of complex rules created by the irrigation community. Because water is a limited common-pool resource in arid environments, rules need to be created concerning who receives water and when. In a top down system, government institutions, which were argued to be unbiased, were seen as the solution to equitably distribute water (Clark 1974; Ostrom 1993). In many of these bottom-up cases, regular meetings concerning rules of water allocation and face-to-face contact among those drawing off the irrigation system were key to enforcing rules of water distribution and to punishing those who attempt to cheat the system.

Ostrom and Gardner (1993), for example, point to two state-managed irrigated systems in Nepal that highlight the importance of community-based institutions, which enforce rules concerning the distribution and allocation of water. In one irrigated system, the Nepalese government invested millions of dollars in the construction of concrete-lined canals to feed water to newly available irrigated lands. Project managers, however, focused mainly on main and distributory canals with little thought regarding constructing and maintaining the field canals that were feeding water to the agricultural fields. Additionally, no social institutions were established to distribute water in times of low streamflow. These failures resulted in a high incidence of conflict and little equity in how water was distributed across the irrigated landscape. In another state-managed system, however, one farmer took the initiative to organize farmers into committees to create rules concerning the use of irrigation water. In effect, this state-created irrigation system became managed from the bottom-up and resulted in a mostly equitable distribution of water and higher agricultural productivity. Regular communication created rules that effectively managed the system, and face-to-face interaction allowed for cheaters of the system to be identified and sanctioned. It is clear from these divergent Nepalese examples and the Balinese system, that the rules of water distribution and allocation are highly diverse and dependent on the local socioecological conditions of the irrigated system.

Considering the Scale of the Irrigation System and Management

Scale is important to consider when thinking about the management of canal systems, and from the archaeological case studies above, the larger systems are more centrally managed. Hunt (1988), however, has provided multiple ethnographic examples approaching a half a million hectares of irrigable land that are managed at both the national and community level. Irrigated acreage estimates are highly unreliable however, since fallow schedules could mean that as much as half of the land may not be under cultivation and irrigated acreage could change through time depending on the needs of the population (Gibson 1974). Irrigated acreage in Mesopotamia may have been quite a bit larger than half a million hectares, though, so Hunt's arguments may not apply to this case study and be more relevant to larger modern systems. Mesopotamian irrigation, however, did function for long periods of time and combatted naturally high salinity at most other times in its history, prompting archaeologists to link the centralization of management to soil degradation. This hypothesis certainly deserves to be tested further with direct data from soils from comparative bottom-up and top-down management regimes.

Additionally, the above discussion illustrates the importance of the creation of appropriate institutions in managing water and agriculture in irrigated systems. These institutions are highly diverse, dependent on individual irrigation systems, and relegated by the scale of the system. Archaeological evidence clearly demonstrates that the Hohokam of the Phoenix Basin created relationships along canal systems, which likely supported institutions that regulated water distribution. Less evidence is available concerning how institutions were created on the north coast of Peru, but clearly, their rules concerning water distribution functioned for a long period of time in those fields not under direct control of the Chimú Empire. In Mesopotamia, however, bureaucrats, who were not directly involved in farm management, managed these institutions, and technologies to prevent ecological problems in the agricultural fields were not used in time to prevent the collapse of major cities.

Modern irrigated systems should heed these lessons from the archaeological case studies. Institutions need to be created, or at least, based at (or at least with the involvement of) the community level, and it is clear that there is no “one size fits all” solution. Individual farmers should be involved in decision-making concerning their agricultural fields and the distribution of water, since they are familiar with the function of their agroecosystem and can communicate with fellow users who share the water with them. While centrally-managed systems have become the status-quo in the countries with the most irrigated acreage, including the United States, Pakistan, and China, potential exists to incorporate farmers into their management, as seen in Nepal and the Colorado River (although that path was not chosen in the latter case). From the archaeological case studies presented here, long-term sustainable irrigated systems are possible. Both ecological and social solutions to failing irrigated systems are known and supported in archaeological and ethnographic case studies across the world. While these solutions are difficult to create and are highly localized, efforts can be made to ensure that these irrigated systems can feed the world’s population in perpetuity.

Chapter 8

CONCLUSIONS AND FUTURE DIRECTIONS

This dissertation has examined how the intensification and longevity of ancient irrigated systems affected agricultural soils in two arid regions of the world that supported large prehispanic populations. The main question addressed by this research is, *what is the relationship between the longevity and intensification of irrigation agriculture and soil quality?* To answer this question, a unique methodology was created to identify and sample prehistoric and historic agricultural fields in the Phoenix Basin and coastal Peru to understand how soils can be altered in a variety of contexts under which large-scale irrigation is managed.

Using data from soil samples from prehistoric and historic agricultural fields, I have argued that farmers in the Phoenix Basin and the north coast of Peru incorporated agricultural strategies to enhance certain characteristics of the soil for hundreds of years. These strategies to maintain or enhance soil quality included sedimentation, the use of ridges and furrows to control salts, and frequent leaching of fields. These case studies diverge, however, when the effects of the intensification of agriculture are compared. The intensification and longevity of irrigation in the Phoenix Basin did, in fact, enhance many of the soil characteristics important for crop growth, including total nitrogen and organic carbon. While coastal Peruvians created a largely sustainable system for many centuries, intensively used state-controlled fields show mixed signs of degradation – one walled field shows evidence for erosion, while another shows serious signs of degradation-hundreds of years after their abandonment.

The results from both regions show that, like dry-farmed soils, agricultural soils in irrigated systems are also highly susceptible to degradation under intensive and long-term agriculture and strategies are needed to replace nutrients lost to harvest. Irrigated systems are the most intensive agricultural system in arid environments, so they are especially vulnerable to soil degradation, including salinization.

Significance of Research

The interdisciplinary datasets collected and analyzed to address anthropological questions concerning these irrigated agroecosystems provide a holistic view of two irrigated agricultural regions in different parts of the world. By examining the social and ecological consequences of long-term irrigation and agricultural intensification, we can begin to understand how these activities can have both positive and negative consequences for the long-term sustainability of soils in irrigated agricultural fields. This analysis has shown that salinization was not a problem in either region of the world in the past, despite hypotheses that soil degradation may have led to major cultural transformations (e.g., the collapse of the Hohokam). This dissertation has also attempted to clarify how long-term and intensifying agriculture affected soils and how this research can inform both archaeological and modern case studies.

As described in Chapter 2, many of our interpretations concerning how long-term irrigation affects soils are based on proxy data, like historic documents showing a shift to more salt-tolerant crops, but not on actual soils data. Due to a lack of an appropriate methodology to locate and sample buried ancient irrigated sediments, soils data are largely lacking in archaeological irrigated contexts. This dissertation, then, provides a framework for sampling surface and buried irrigated fields in multiple regions of the world. If modern forces, like urbanization, have not destroyed ancient irrigated sediments, they can be identified, sampled, and analyzed to increase our understanding of the relationship between long-term irrigation and soil quality. If this analysis can be replicated with other sediments that have been irrigated for centuries, a more complete view of the appropriate management strategies for irrigated soils can be accurately identified. Three key aspects of sampling in ancient agricultural landscapes need to be considered – the classification of different geomorphic surfaces, the identification of other factors that may be altering soil characteristics (e.g., modern agricultural use), and the finding of appropriate control samples to understand how long-term irrigation affected the natural state of the soils.

Considerations for Sampling Archaeological Irrigated Landscapes

Many of the challenges confronted the analysis of agricultural soils in both the Phoenix Basin and the north coast of Peru need to be considered when proposing a general framework for studying irrigated soils. The regions addressed in this dissertation provided two unique contexts for sampling in an ancient irrigated system. On the Pampa, fields were largely located on the surface, while the middle Gila River fields were buried under a meter or more of soil. Sampling proved to be particularly challenging for the middle Gila River, which has been subject to a variety of anthropogenic and natural forces that could influence soil formation. Both regions, however, have been useful in identifying the important aspects to consider when identifying fields and sampling soils in ancient irrigated landscapes.

As discussed throughout the dissertation, considering the *geomorphic context* of the agricultural field is essential in comparative soil analysis. A wide variety of geomorphic contexts, however, can make it difficult to find a large enough sample size within each separate context. For this reason, performing an in-depth analysis of the geomorphic context and landscape formation factors before selecting sampling sites can ensure that a large enough sample is collected in each context. Fortunately, analysis and mapping of geomorphology was already done across the entire GRIC, making it easy to locate samples in the two different geomorphic contexts – the Holocene and Pleistocene Terraces. On the Pampa, however, geomorphic sampling and identification had been done fairly recently on a small part of the Pampa, and sampling of agricultural fields took place on a much larger scale. Thus, information on geomorphology was only available for a small percentage of the fields sampled, and much of the geomorphic assignments to each field took place after fieldwork was completed. This lack of extensive geomorphic data at the time of sampling complicated the methodology, limited extensive sampling in multiple areas, and resulted in low sample sizes for certain field types. For example, more extensive geomorphic analysis may have located long-lived fields in the same context as the early abandoned Sicán fields on the Pampa. These Sicán fields are likely key in understanding the successful and unsuccessful irrigation strategies that resulted in their abandonment, but the inability to locate fields in a similar geomorphic context restricted interpretations concerning these fields.

In addition to the geomorphic context, it became clear while sampling on the middle Gila River that numerous other factors, including *modern land use*, may also be driving soil formation and clouding our understanding of the anthropogenic impacts of the soil. For this reason, the natural and anthropogenic factors that may be affecting soil characteristics need to be outlined and considered when analyzing and interpreting soil characteristics. For example, many ancient agricultural fields on the GRIC were buried under a modern agricultural field. These modern agricultural fields result in the addition of water and nutrients that may leach to the abandoned prehistoric or historic fields, which may alter the soil characteristics and conceal the signature from prehistoric or historic land use. It was then essential to consider the impact of these other landscape uses when interpreting the soil characteristics of the prehistoric and historic fields.

Finally, the importance of locating reliable control samples in identifying the anthropogenic impact on soils has been highlighted in this and previous studies of ancient agricultural soils (Sandor and Homburg 2010). In irrigated landscapes, it can be particular hard to locate control samples, because they have been subject to long-term and extensive human use. For example, on the GRIC, control samples were collected in areas in between large distributory canals, which were not used to directly feed water to agricultural areas. These locations, however, were hard to locate due the palimpsest of agricultural use for thousands of years on the middle Gila River. For example, the control samples for each geomorphic context on the middle Gila River were collected from one location on the entire GRIC, due to their unavailability elsewhere on the GRIC. These highly localized control samples led to a limited understanding of the characteristics of the natural landscape - especially those analyses on soil texture - and thus restricted the ability to make firm interpretations on how the landscape was altered by long-term irrigation. Appropriate control samples were also not located on the Pampa, restricting the ability to understand how prehispanic irrigation truly altered the original quality of the soil.

Future Research Ideas for Sampling on the Pampa de Chaparrí

Despite its challenges, analyzing ancient irrigated systems can be particularly useful, since so little research has been done on the relationship between long-lived irrigation systems and soil quality. It can, however, be difficult to make solid interpretations without considering the complicating factors listed above. The soils results from the Pampa de Chaparrí proved to be particularly mixed, in part because sampling was designed as a pilot study for future work on the Gila River Indian Community and its analysis clarified the methodology needed for ancient irrigated fields. The results concerning soils on the Pampa, however, provide useful future directions for sampling this landscape.

First, the soil characteristics of total nitrogen show that nutrient inputs would have been needed on the Pampa prehispanically to maintain crop production for hundreds of years. Historic and archaeological research indicates that nutrient inputs are possible from three sources on the north coast of Peru – sedimentation from irrigation canals, seabird and bat guano, and/or camelid dung. While pilot analysis of nitrogen isotopes on agricultural soils on the Pampa does not support the hypothesis that bat guano or camelid dung were used on the Pampa, more extensive sampling and analysis of nitrogen isotopes in the soil could firmly establish the types of fertilizer used on the Pampa prehispanically. Despite the lack of evidence for animal fertilizer, sedimentation was observed in highly localized contexts on the Pampa, although infrequently observed in the surface fields, perhaps due to their susceptibility to post-abandonment erosion of the Pampa. Because a buried anthropogenic deposit was found in the cut of a recent arroyo, indicating sedimentation was occurring in this part of the Pampa, auguring in other areas where an anthropogenic deposit could be buried would be useful in understanding its extent across the entire Pampa. A combination of both surface and buried sampling is key, as done with the GRIC case, to ensure that all irrigated fields are located and sampled, instead of just the highly visible surface fields.

Another strategy to clarify the relationship of soils and the irrigated landscape would be to analyze how soils in fields vary based on their relationship to large administrative sites and the comparison of upstream and downstream fields. Chapter 7 highlighted the importance of considering the extent to which management was centralized in considering the sustainability of irrigated systems. The methodology used on the Pampa, however, restricted the ability to test this hypothesis. Both Hayashida (2006) and Ertsen (2010), however, have hypothesized that fields upstream on the Pampa were likely managed directly by the state, while those fields downstream remained under control of the individual household. Sampling fields based on the model proposed by Hayashida (2006) and Ertsen (2010) could add to the sample size of the intensively used walled fields and clarify how different forms of irrigation management may have altered soil quality.

Finally, modern vegetation sampling (see Hall et al. 2013 for an example of this on an archaeological landscape) may highlight the legacies of long-term irrigation on the Pampa and clarify the results of the soil analysis. Because of the lack of occupation and use of the Pampa since abandonment in the early AD 1500s, vegetation identification and sampling could reflect the results of prehispanic land use. For example, during soil sampling of the Pampa in 2009, marked vegetation differences were observed between walled and unwalled fields and in the early abandoned Sicán fields. Unfortunately, this sampling strategy was not included in addition to the soil sampling, due to lack of time and funds. Future analysis of how vegetation differs across the modern Pampa landscape may clarify the soil analyses in contexts that can be difficult to interpret due to low sample size.

Significance of this Research for Modern Irrigated Agriculture

The conclusions of this research have significant theoretical and methodological implications for the modern irrigated systems, even though many of them operate at a much larger scale than those addressed in this dissertation. Many of the irrigation systems that have seen the most expansion, growth, and intensification are in countries that manage their systems at a highly centralized level (China, USA, Pakistan). These cases show that if farmers are removed from the direct decision-making process, those administrators of the system should be aware of the necessity of these strategies and attempt to incorporate them into the irrigated systems.

What, then, have we learned from the archaeological case studies presented in this dissertation for the future of modern irrigation agriculture? First and foremost, agricultural strategies, like leaching of fields and sedimentation, are essential in maintaining soil quality for the long-term. While farmers around the world have known these strategies for thousands of years, however, these strategies are frequently not implemented when problems arise. This lack of implementation shows that the degradation of soils in irrigated environment is a social issue, as well as an ecological problem.

Times of low water flow present a specific challenge to maintain soil quality, if excess water cannot be applied to the irrigated system to leach fields and apply sediments in time of fallow. Excess water is needed at the correct time to ensure that soils are leached of any accumulating salts, and if excess water is not available, salts need to be combated in other ways or will simply accumulate in the soil, severely limiting the ability to successfully cultivate crops. Ethnographic documents indicate that this lesson was certainly learned on the GRIC in the late AD 1800s and early 1900s when the loss of water on the middle Gila River prevented the leaching of fields, and the alkalization of fields became a serious problem (DeJong 2011; Southworth 1919). The analyses of soils presented in this dissertation show low levels of electrical conductivity and sodium adsorption ratio in prehistoric and historic fields, indicating that prehistoric and historic farmers effectively managed and prevented the accumulation of salts and sodium in their agricultural fields. These strategies were not continued, however, when these farmers lost control over the water on the middle Gila River.

Implications for the Gila River Indian Community

With the water settlement granted to the members of the Gila River Indian Community in 2004, this research has important implications for the expansion of farming and water use along the middle Gila River and for the documentation of the GRIC's agricultural history. As the GRIC moves forward with plans to expand irrigated acreage across the reservation today, ancient agricultural fields will be destroyed. These fields were recorded through this dissertation research, providing valuable archaeological data on ancient agricultural fields across this landscape.

This research is then relevant to interpretations of the sustainability and resilience of the GRIC landscape to long-term irrigation. As more lands come under cultivation over the following decades, interpretations of the sustainability of the farming and irrigation can have implications for continuing agricultural development of the landscape, which this dissertation addresses. There is no doubt that these irrigation systems are designed to intensively cultivate crops and are hoped to sustain that production for the long-term, which these fields have done in the past. The means of water delivery, however, has drastically changed since the prehistoric and early historic fields were farmed with the GRIC now receiving the vast majority of its water from the Central Arizona Project canal, fed by water from the Colorado River (DeJong 2007). Colorado River water today presents major obstacles to sustainable agriculture on the middle Gila River including, the lack of suspended sediments needed to maintain soil quality and frequently and the shortage of water necessary to flush salts from the soil.

Unlike the middle Gila River prehistorically and historically, the Colorado River supplies water to almost 5.5 million acres of agricultural land to 7 states and 22 Native American tribes. In addition, 40 million people rely on water from the Colorado River for municipal purposes, including drinking water, and it produces 4,200 megawatts of hydroelectric power for use across the American West (The United Stated Department of the Interior 2012). The possibility of managing the Colorado River's water, which has been greatly overpromised to users across its watershed in the past decades, at a bottom-up level is extremely complicated due to its sheer size and the number of users that need to cooperate in the face of future shortfall (see the discussion of the relationship of scale and management in the previous chapter). Top-down management of the Colorado River provides a centralized source of decision-making and enforcement to ensure that disputes over water are resolved among multiple states and countries.

Thus, the United States federal government, which has formulated agreements and treaties concerning the river water among Mexico, the states of Colorado, Arizona, and California, and numerous Native American tribes, largely manages the Colorado River. The federal government has invested millions of dollars into the construction of infrastructure, including thousands of miles of canals, and the management of the distribution of water (Hundley 2009; Meyers and Noble 1967). Despite the massive amount of investment, the management of the Colorado River is seen as problematic by ecologists and sustainability scientists in terms of environmental sustainability and environmental justice (Brownell and Eaton 1975; Gleick 1988; Glenn et al. 1996; Pitt et al. 2000). Thousands of hectares of fields around the Colorado River have been highly salinized, and predictions of major water shortages loom in the near future, which will exacerbate both salinization and conflicts over who receives water (Gardner and Young 1988; Ward 2003). Despite the promise of bottom-up management described in the previous chapter, this system would be extremely difficult to manage from a bottom up level due to its size and the number of stakeholders (although some sustainability scholars claim otherwise, see van Schilfgaarde 1994 and Wichelns and Oster 2006). GRIC will need to be highly involved in communicating with the managers of the Colorado River, many of whom are based in Washington, DC, to ensure that they can incorporate strategies to flush salts into their system. They will also need to have an in depth plan for preserving water within their allotment of 311,800 acre-feet of water per year to allocate to field leaching instead of simply crop production.

Additionally, the water that the GRIC will be receiving from the CAP canal will have a lack of sediments suspended in the water. As seen in the increase in total nitrogen and organic carbon, in addition to the deposition of new silts and clays in prehistoric and historic fields, sedimentation was an important driving process for the anthropogenic soil formation in the past across the GRIC. The prehistoric and historic canals carried suspended loads of sediments, nutrients, and organic matter that effectively maintained soil quality over time. Modern canals, however, do not carry these suspended loads of sediments, since their water source is different from prehistoric and historic canals. It will be important to consider how soil fertility, in the form of organic matter, nitrogen, and carbon, can be maintained, if the irrigation water from modern canals does not carry suspended loads of sediments as they did in the past. The addition of chemical fertilizers is modern solution to this problem that farms on the GRIC are already using, but fertilizers carry their own risks in decreasing water quality and may force the farmer to become dependent on these additional purchases of fertilizer over time.

Future Directions and Final Thoughts

This dissertation asserts that, overall, the farmers in the Phoenix Basin and the north coast of Peru properly managed soil quality in their agricultural fields for centuries with the use of strategies that controlled salt accumulation and added nutrients and organic matter. While other case studies have faced serious problems with salinization of agricultural fields, including Mesopotamia and the modern Colorado River, the irrigated systems in the Phoenix Basin and the north coast of Peru created long-term success in maintaining agricultural production. This research has important implications for modern systems today, which are aware of the technologies available to prevent salinization and waterlogging, yet still result in soil degradation.

This dissertation has also demonstrated the importance of considering the social and economic aspects of the irrigation system when maintaining agricultural production over the long-term. While ecological solutions to combat salinization and other forms of soil degradation are known to farmers across the worlds, considering the appropriate social and economic contexts is essential in ensuring that these strategies are incorporated correctly. It is clear that the sustainability of a large-scale irrigation system does not just require ecological solutions, but also social solutions. Archaeological case studies of irrigated systems can be of great benefit to ensuring the longevity of the world's expanding and intensifying irrigation agricultural systems.

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APPENDIX A

SAMPLING SITE DESCRIPTIONS FOR THE MIDDLE GILA RIVER

The following pages provide site descriptions and soil description forms for all of the sampled sites on the Gila River Indian Community. The table s provide soil observations made in the field. Blank cells indicate that the characteristic was not observed in the field at that time. All codes have been provided in Appendix A. Any maps were created by GRIC, and specific locations have not been provided in order to protect the archaeological deposits. The site number, alternate site name, locus, feature, and specimen numbers are for internal GRIC-CRMP databases and reports. The GRIC Numbers, age of field, associated canal, parent material, and comments were all observations and notes made during field sampling.

Sampling areas at GR 1157 and GR 919 are not described here, as they have been described in great detail in Sandor's sampling report for the Gila River Indian Community (2010). All raw soils data is stored with the Digital Archaeological Record (tdar.org).

GR 1055

Site: GR 1055

Alternate Site Name: Cecelia Martinez Home Site

Locus: B

Specimen Numbers: 440-458, 422-435

GRIC Numbers: 6-24, 90-103

Age of Field(s): Historic

Associated Canal: Canal Baseline

Landform: Holocene Terrace

Feature Number(s): 33

Comments:

- Used to be under an historic house, but surrounded by modern fields at time of sampling. Sampling area, however, has not been farmed recently.
- Sampling site located near the confluence of the Salt and Gila Rivers, and historic and prehistoric canals in the area were fed off the Salt River.
- One prehistoric canal was located, but many historic canals found and field deposit was located in associated with the historic canals.
- Lots of surface disturbance, but field located well below surface.

Table A.1: Soil Description Form for GR 1055

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-32	A_p	AS	7.5 YR 5/4	7.5 YR 4/4	Silty Clay	Gravels	1
2	32-57	A_1	CS	7.5 YR 5/4	7.5 YR 3.5/4	Silty Clay Loam		
3	57-71	AC_1	CS	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		
4	71-87	AC_2	CS	7.5 YR 5.5/4	7.5 YR 4/4	Silt Loam		
5	87-101	C_1	CW	7.5 YR 7/4	7.5 YR 4/4	Silt Loam		
6	101-125	C_2	CS	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		
7	125-144+	C_3	-	7.5 YR 6/4	7.5 YR 4/3	Silt Loam		

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	M - C	Sbk - Pl	VH	Fi	VS	VP			
2	2	M - C	Sbk	H	Fi	VS	P			

3	1	F - M	Sbk	S	Fr	SO	SP				
4	1	M - C	Sbk	SH	Fr	SO	SP				
5	0	0	MA	S	Fr	SO	PO				
6	0	0	MA	S	Fr	SO	PO				
7	0	0	MA	SH	Fr	SO	PO				

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1					$CaCO_3$	moderate	white	flecking				
2					$CaCO_3$	few	white	flecking				
3					$CaCO_3$	very few	white	flecking				
4					$CaCO_3$	very few	white	flecking				
5												
6												
7												

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	VF - F			8	VE	40	very hard, clayey
2	2	VF			8	VE	28	
3	1	VF			8	ST	12	parting to Massive Structure
4	1	VF			7.5	ST	11	parting to Massive Structure
5	1	VF			8	ST	9	increase in fine sands
6	1	VF			8	ST	8	harder on profile face
7	-	-			8	ST	6	

GR 738

Site: GR 738

Alternate Site Name: Reed 4 Agricultural Development Site

Locus: B

Specimen Numbers: 36-73

GRIC Numbers: 140-161 (controls), 162-183 (prehistoric field)

Age of Field(s): Prehistoric

Associated Canal: Old Santan Canal

Landform: Holocene Terrace

Feature Number(s): None assigned.

Comments:

- Prehistoric agricultural field discovered during the excavation of a modern agricultural field.
- Control samples were located in an area where no prehistoric or historic agricultural features were found.
- Prehistoric sherds were found in the prehistoric canals and agricultural field deposit.
- Small field lateral was found, and samples were collected close to that lateral, since that canal would have been directly feeding the field.

Table A.2: Soil Description Form for GR 738 (Prehistoric Field)

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-31	A_p	AS	7.5 YR 6/3	7.5 YR 4/3	Silt Loam	Gravels	1
2	31-61	AB	CS	10 YR 6/3	10 YR 4/4	Silt Loam	Gravels	1
3	61-82	BC1	CS	10 YR 7/3	10 YR 5/4	Silt Loam		
4	82-121	BC2	GW	10 YR 6/3	10 YR 4/4	Silt Loam		
5	121-160+	C	-	7.5 YR 7/3	7.5 YR 4/4	Silt Loam		

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	2	M-C	Sbk	H	Fi	MS	MP			
2	2	F-M	Sbk	H	Fi	MS	MP			
3	1	F	Sbk	SH	Fr	SS	SP			
4	1	F	Sbk - MA	SH	Fr	SS	SP			
5	0	0	MA	SH	Fr	SS	NP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Shape
1												
2												
3					$CaCO_3$		white	filaments				
4					$CaCO_3$		white	filaments				
5					$CaCO_3$		white	filaments				

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	2	VF – F			8	VE	25	Disturbed modern plow zone.
2	1	VF			8	VE	27	Prehistoric Field.
3	1	VF			8	SE	22	
4	1	VF			8	SE	16	
5	0	-			8	VE	15	

Table A.3: Soil Description Form for GR 738 (Control Samples)

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quan tity**
1	0-39	A_p	AS	7.5 YR 6/3	7.5 YR 4/3	Silt Loam	Gravels	1
2	39-73	AC	AS	10 YR 7/3	10 YR 4/4	Silt Loam	Gravels	1
3	73-112	Bk	CS	7.5 YR 6/4	7.5 YR 4/4	Silt Loam	-	-
4	112-150+	C	-	7.5 YR 7/3	7.5 YR 4/3	Silt Loam	-	-

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	2	M	Sbk	VH	Fr	SS	SP			
2	1	M	Sbk	SH	Fr	SS	NP			
3	1	M	Sbk	VH	Fi	S	P			
4	0	0	MA	SH	Fr	SS	SP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Shape
1												
2					$CaCO_3$		white	Filaments				
3					$CaCO_3$		white	Nodules				
4					$CaCO_3$		white	Filaments				

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	VF - F			8	ST	20	Firm, but disturbed.
2	1	VF			8	ST	15	Sampled for controls
3	0				8	VE	24	Vertical cracking.
4	0				8	VE	18	

GR 9117 and 9118

Site: GR 9117 and 9118

Alternate Site Name: Pima Lateral Canal, Pima-Maricopa Irrigation Project

Locus: None.

Specimen Numbers: 35 – 62 (GR 9117) and 74-93 (GR 9118)

GRIC Numbers: 83-120 (GR 9117) and 63 – 82 (GR 9118)

Age of Field(s): Prehistoric (9117) and Control Samples (9118)

Associated Canal: Pima Lateral

Landform: Pleistocene Terrace

Feature Number(s): Features 9 and 10

Comments:

- Site GR-9117 (Figure 5.4) contained a prehistoric agricultural deposit in a trench that was sampled during pilot research. A large prehistoric canal was located in this trench, making the presence of prehistoric fields likely.
- In an adjacent trench, a small field lateral, which would have directly fed water to the fields, ran perpendicularly to the large canal (Masse 1981; Woodson and Huckleberry 2002; Woodson 2003 for descriptions of canal hierarchy).
- Dark, organic soil, high in fine sediments like clay and silt, was present below the surface and adjacent to where the canal fed the agricultural fields in the past (see A Horizon, Buried Prehistoric Field in Figure 2). Because of the

characteristics of the soil profile and the proximity to the canal (both horizontally and vertically in the profile), this stratum is interpreted as a prehistoric field surface.

- The stars in Figure 5.4 note where samples were collected in both a horizontal row and vertical column.
- Redwares and plainwares were found in canals and field deposits.
- GR 9117 was located at the edge of a modern cotton field.
- Control samples were also collected from a trench at GR-9118, a site approximately 500 meters from GR-9117 and in the same geomorphic context. This trench exposed three large prehistoric distributory canals. These distributory canals do not directly feed fields but transport water to smaller canals and field laterals (Masse 1981; Woodson and Huckleberry 2002; Woodson 2003). Because three of these distributory canals are located in one 25-meter trench, this area is most likely not a prehistoric field, but instead served as an area where water was being delivered to the agricultural fields further downslope

Table A.4: Soil Description Form for GR 9117

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-28	Ap1	AI	7.5 YR 6/3	7.5 YR 4/3	Silty Clay	Gravels	20%
2	28-68	Ap2	VA	7.5 YR 6/4	7.5 YR 4/4	Silty Clay	Gravels	30%
3	68-98	A	CS	7.5 YR 5/3	7.5 YR 4/3	Loam	Gravels	5-10%
4	98-126	BA	CS	7.5 YR 6/3.5	7.5 YR 4/3	Loam		
5	126-155	Bk1	GS	7.5 YR 5/4	7.5 YR 4/4	Silty Clay		
6	155-185+	Bk2	-	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	F-M	CDY-Sbk	SH	Fr	SS	SP			
2		0	MA	SH	Fr	SS	SP			
3		0	MA	SH	Fr	SS	SP			
4		0	MA	SH	Fr	SS	SP			

5		0	MA	SO	VFr	SS	SP			
6		0	MA	SH	Fr	SS	SP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2												
3												
4												
5												
6												

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	3	VF				VE		Anthropogenic canal cut and

								fill
2	3	VF				ST		Chunks of carbonate (from canal?)
3	1	VF				ST		Prehistoric field
4	1	VF				ST		
5						VE		
6						VE		Powdery carbonate at base

Table A.5: Soil Description Form for GR 9118 (Control Samples)

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-28	Ap1	AS	7.5 YR 5/3	7.5 YR 4/3	Silty Clay	Gravels	5%
2	28-61	Ap2	VaS	7.5 YR 4/3	7.5 YR 4/3	Clay Loam		10%
3	61-80	AB	CS	7.5 YR 6/3.5	7.5 YR 4/3.5	Silty Clay		5%
4	80-94	Bk1	GS	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		5%
5	94-133	Bk2	GS	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		5%
6	133-160+	Bk3	-	7.5 YR 6/4	7.5 YR 4/4	Silt Loam		5%

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	1	M-C	Sbk	H	Fi	S	P			
2	1	M-C	Sbk	H	Fi	S	P			
3	0		MA	SH	Fr	MS	SP			
4	0		MA	SH	Fr	SS	SP			
5	0		MA	SO	VFr	SS	SP			
6	0		MA	SO	VFr	SS	SP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Sha pe
1					$CaCO_3$	loose	White	Gravel				
2					$CaCO_3$		White	Nodules				
3					$CaCO_3$	Few	White	filaments				

4					$CaCO_3$	Soft	White						
5													
6													

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	1	VF				VE	28	
2	1	VF				VE	28	
3	1	VF				ST	21	Sampled for controls.
4	1	VF				ST	17	
5	1	VF				ST	13	
6						ST	13	

GR 931 (Historic)

Site: GR 931

Alternate Site Name: Nelson Road Site

Locus: 4

Specimen Numbers: 785 – 812

GRIC Numbers: 104 - 131

Age of Field(s): Historic

Associated Canal: Old Mount Top Canal, field lateral present between trenches 205 and 206

Landform: Holocene Terrace

Feature Number(s): None assigned.

Comments:

- Site has been partially disturbed due to unauthorized grading of the landscape.
- Samples were not collected in areas that had been recently graded.
- Trenches were excavated to assess the impact of the graders (half in the area of grading, half outside)
- Fields have not been farmed since at least 1950 - mesquite stumps are present at the surface indicating that the land was never mechanically plow, and in fact hand cleared for agriculture.
- Fields fed by the Old Mount Top Canal with a field later coming off the canal between trenches 205 and 206 (sampling occurred in trenches 205, 206 and 207).

- Because fields are near the surface, I collected as close to the surface as possible, without collecting areas of modern disturbance – near the bottom boundary of A horizon.
- Old Mount Top Canal was constructed in the early 1800s and abandoned in 1866 (Southworth 1919)
- Previous archaeological investigations have shown seasonal use during the prehistoric period, but more intensive use during the historic O’odham period, as villages moved toward the center of the reservation in response to Apache raids (Eiselt et al. 2002; Neily 1991; Ruppé 1962; Wood 1972; Woodson 2000, 2002)

Table A.6: Soil Description Form for GR 931 (Historic)

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	**Moist**		**Size**	**Quantity**
1	0-2	Ap1	AS	7.5 YR 5/3	7.5 YR 3/3	Silt Loam	Gravels	1
2	2-15	Ap2	AS	7.5 YR 5/3	7.5 YR 3/3	Silt Loam		
3	15-31	A1	CS	7.5 YR 5/3	7.5 YR 3/3	Silt Loam		
4	31-66	AB	CS	7.5 YR 4/3	7.5 YR 3/3	Silt Loam		
5	66-95	Btkn1	CS	7.5 YR 5/3	7.5 YR 3/3	Silty Clay Loam		
6	95-126	Btkn2	CS	7.5 YR 6/3	7.5 YR 4/3	Sandy Loam		
7	126-150+	Ck	-	10 YR 5.5/3	7.5 YR 4/4	Sandy Clay Loam		

	Structure			Consistence				Mottles		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	M	Pl							
2	3	M	Sbk - Pl							

3	2	M	Sbk - Pl							
4	3	M	Sbk							
5	1	M	Pr							
6	1	M	Pr							
7	-	-	MA							

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2												
3												
4												
5												
6												
7												

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	VF				ST		disturbed, graded area
2	3	VF				VE		
3	2	VF				ST		historic field sampling stratum
4	1	VF				ST		
5						VE		
6						ST		2 cm clay stratum found at the bottom of this stratum
7						ST		

GR 643

Site: GR 643

Alternate Site Name: Parsons 6 Agricultural Development Site

Locus: None.

Specimen Numbers: 18-47 (Prehistoric), 160-203 (Historic and Controls)

GRIC Numbers: 240-254 (Prehistoric), 255-265 (Controls), 266-276 (Historic)

Age of Field(s): Two Separate Prehistoric and Historic Field Strata

Associated Canal: Prehistoric and Historic Lower Santan Canals

Landform: Holocene Terrace

Agricultural Field Feature Number(s): 4 (Prehistoric) and 11 (Historic)

Comments:

- Prehistoric Field Area
    - Located close to a modern house
    - Field stratum located next to prehistoric canal. Both features have prehistoric sherds embedded in them.
    - Area not on Southworth's 1914 maps and has no evidence for recent agricultural use.
    - Field horizons here located on each side of the large canal and are very thick (~50 cm).
- Historic Field Area and Control Samples

- Trenches were located to the south of where the prehistoric fields were found.
- Control samples were collected in areas in between large distributory canals found in one trench, similar to the procedure at GR 9117 and 9118.
- Modern farming is occurring directly to the south, but not in this sampled area.
- Field stratum is laminated, darker in color, and located next to an historic branch canal.

Table A.7: Soil Description Form for GR 643 (Prehistoric)

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-58	A_p	AS	10 YR 5/4	10 YR 3/3	Silt Loam	Gravels	Few
2	58-72	A1	AW	10 YR 4/3	10 YR 3/3	Silt Loam	None	0
3	72-112	A2	AS	10 YR 4/4	10 YR 3/3	Silty Clay	None	0
4	112-147	BC	CS	7.5 YR 6/4	7.5 YR 4/3	Silt Loam	None	0
5	147-150+	C	-	7.5 YR 6/4	7.5 YR 4/3	Silt Loam	None	0

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	M	Sbk	VH	Fr	MS	MP			
2	2	F-M	Sbk-Gr	SH	Fi	S	P			
3	2	M	Sbk	VH	Fi	S	P			
4	2	M	Sbk - MA	SH	Fr	SS	SP			

5	0	0	MA	S	Fr	SS	SP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1					$CaCO_3$	few	white	flecking				
2					$CaCO_3$	many	white	Filaments				
3					$CaCO_3$	many	white	Filaments				
4					$CaCO_3$	Many	white	Filaments				
5					$CaCO_3$	Many	white	Filaments				

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	2	M - F - VF					21	Disturbed modern plow zone.
2	2	VF					25	Thin sand lens on bottom.
3	1	VF					29	Prehistoric Field
4	0	-					20	Some clay pockets
5	0	-					15	Uniform.

Table A.8: Soil Description Form for GR 643 (Historic)

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-20	A_p	AS	10 YR 5/3	10 YR 3/3	Silt Loam		
2	20-62	A1	AS	10 YR 5/3	10 YR 3/3	Silt Loam		
3	62-95	A2	CW	10 YR 6/4	10 YR 4/4	Silt Loam	Gravels	Very Few
4	95-115	C1	CW	10 YR 5.5/4	10 YR 4/4	Silt Loam	-	-
5	115-150+	C2	-	10 YR 6/3	10 YR 5/4	Silt Loam	-	-

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	M	Sbk – Pl	L	Fr	MS	MP			
2	3	C	Sbk	H	Fi	SS	SP			
3	2-3	M	Sbk	H	Fi	SS	SP			
4	3	M	Sbk - MA	H	Fi	NS	NP			
5	0	0	MA	SH	Fr	SS	SP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2												
3												
4												
5					$CaCO_3$			filaments				

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	3	F - VF					15	Disturbed modern plow zone.
2	3	VF – F - M					11	
3	1	M					16	Historic Field
4	1	VF					8	
5	0	-					9	

GR 1530

Site: GR 1530

Alternate Site Name: David Johnson 4 Agricultural Development Site

Locus: None.

Specimen Numbers: 9-38

GRIC Numbers: 216-230

Age of Field(s): Prehistoric

Associated Canal: Blackwater Canal, field lateral (Feature 2, Trench 1) and distributory canal (Feature 3) are overlapping in trench profiles

Parent Material: Old Pleistocene Terrace Remnant

Agricultural Field Feature Number(s): 4

Comments:

- No evidence for historic cultivation on Southworth maps.
- Modern surface appears undisturbed, not farmed recently – mostly desert scrub, with surface disturbance from trucks
- Below disturbance, prehistoric field horizon – higher in clay, not laminated
- Blackwater canal is curving here
- Old Pleistocene Terrace remnant – lots of calcium carbonate leaching, looks like a pretty clay poor system (except in irrigated sediments)

Table A.9: Soil Description Form for GR 1530

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-31	A_p	AS	10 YR 4/3	10 YR 3/4	Silt Loam	Gravels	1
2	31-56	A	VS	7.5 YR 5/4	7.5 YR 4/4	Silt Loam	Gravels	3
3	56-71	AC	AS	7.5 YR 6/4	7.5 YR 4/4	Sandy Loam	Gravels	2
4	71-108	C_1	CW	7.5 YR 6/4	7.5 YR 4/4	Sandy Loam	-	-
5	108-146+	C_2	-	7.5 YR 6/4	7.5 YR 4/6	Sandy Loam	-	-

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	1	M	Sbk - CDY	L	VFr	SS	SP			
2	3	M	Sbk	H	Fi	S	P			
3	1	M	Sbk	S	VFr	SS	SP			
4	3	M	Sbk - MA	SH	Fr	NS	NP			

5	0	0	MA	H	Fi	NS	NP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1					$CaCO_3$		white	flecking				
2					$CaCO_3$		white	nodules				
3					$CaCO_3$		white	nodules				
4					$CaCO_3$		white	nodules				
5					$CaCO_3$		white	concretions				

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	3	M - F - VF			8		16	Disturbed modern plow zone.
2	2	VF - F			8		21	Prehistoric Field.
3	1	VF			8		8	
4	1	VF			8		5	CaCO3 film on surface of profile.
5	0	-			8		8	CaCO3 film on surface of profile.

GR 1532

Site: GR 1532

Alternate Site Name: D Johnson 6 Agricultural Development Site

Locus: None assigned.

Specimen Numbers: 1-30

GRIC Numbers: 277-291

Age of Field(s): Historic

Associated Canal: Canal Blackwater, Canal Azul

Landform: Holocene Terrace

Agricultural Field Feature Number(s): 5

Comments:

- Sampling located in an agricultural field that has been fallow in recent years.
- Many historic (and probably some prehistoric) canals, turnouts, and laterals located during sampling.

Table A.10: Soil Description Form for GR 1532

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-21	A_p	AS	7.5 YR 5/4	7.5 YR 3/3.5	Silt Loam	Gravels	Few
2	21-51	A	AS	7.5 YR 5/3	7.5 YR 3/3	Loam	Gravels	Many
3	51-73	C1	CW	7.5 YR 6/4	7.5 YR 4/6	Sandy Loam	Gravels	Many
4	73-107	C2	CW	7.5 YR 5/6	7.5 YR 5/5	Sandy Loam	Cobbles	Many
5	107-152+	C3	-	7.5 YR 6/4	7.5 YR 6/6	Sandy Loam	Cobbles	Many

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	M	Sbk – Pl	L	Fr	SS	MP			
2	3	M-C	Sbk-Gr	SH	Fi	SS	MP			
3	0	0	MA	H	Fi	SS	SP			
4	0	0	MA	H	Fi	NS	NP			

5	0	0	MA	L	Fr	NS	NP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Shape
1												
2												
3					$CaCO_3$	On profile face	white	film				
4					$CaCO_3$	On profile face	white	film				
5					$CaCO_3$	On profile face	white	film				

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	M – F					16	Disturbed modern plow zone.
2	2	F					13	Prehistoric Field.
3	1	F					9	
4	1	F					6	CaCO3 film on surface of profile.
5	0	-					4	CaCO3 film on surface of profile.

GR 782

Site: GR 782

Alternate Site Name: Edward Marrietta Homesite

Locus: None assigned.

Specimen Numbers: 31-62

GRIC Numbers: 476-489

Age of Field(s): Prehistoric

Associated Canal: Unknown

Landform: Holocene Terrace

Agricultural Field Feature Number(s): 21

Comments:

- Field are well-preserved and are embedded with prehistoric sherds.
- Reservoir located to the north of the fields.
- Sampling area located in a cleared front yard of a house and has not been recently farmed.

Table A.11: Soil Description Form for GR 782

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-28	Ap	AS	10 YR 4/3	10 YR 3/3	Silty Clay	None	None
2	28-64	A	GI, W	10 YR 4/4	10 YR 4/4	Silt Loam	None	None
3	64-95	AB	AS	10 YR 5/3	10 YR 4/4	Silt Loam	None	None
4	95-122	CB	AS	10 YR 6/4	10 YR 4/4	Silt Loam	None	None
5	122-150+	C	-	10 YR 6/3	10 YR 4/4	Sandy Loam	None	None

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	F	Pl-Gr	L	L	VS	VP			
2	3	F	Gr	VH	VFi	MS	VP			
3	2	F	Gr	H	Fi	S	VP			
4	1	F	Gr	H	Fi	S	SP			

5	0	0	MA	Sp	VFr	NS	NP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1					$CaCO_3$		white	nodules				
2					$CaCO_3$		white	Nodules and filaments				
3					$CaCO_3$	Fewer than A horizon	white	Filaments				
4					$CaCO_3$		white	Filaments				
5					$CaCO_3$		white	Filaments				

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	**Size**	**Size**	**Shape**				
1	2	F-M				VE	41	Disturbed modern plow zone.
2	2	VF				VE	22	Prehistoric Field.
3	1	VF				VE	12	Developing B Horizon.
4	0	-				VE	8	
5	0	-				VE	7	

GR 1528

Site: GR 1528

Locus: None.

Specimen Numbers: 30-61

GRIC Numbers: 200 - 215

Age of Field(s): Historic

Associated Canal: Bapchil Canal

Landform: Holocene Terrace

Feature Number(s): 4

Comments:

- Very well preserved and finely laminated.
- Bapchil Canal plotted on Southworth's 1914 maps.
- Flood events to the north of canal were avoided during sampling. It appears as if canal may have protected field deposits from flooding.
- Cleared Area from modern houses, trash area.

Table A.12: Soil Description Form for GR 1528

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-22	A_p	AS	10 YR 6/3	10 YR 4/3	Silt Loam	Gravels	Very Few
2	22-43	A	AS	7.5 YR 5/2	7.5 YR 3/2	Silty Clay Loam	None	None
3	43-82	B1	GW	10 YR 6/3	10 YR 4/4	Silty Clay Loam	Gravels	Very Few
4	82-113	B2	AS	10 YR 6/3	10 YR 4/3	Silt Loam	None	None
5	113-139	C1	AW	10 YR 6/3	10 YR 4/3	Loamy Silt	Gravels	Many
6	139-162	C2	CW	10 YR 6/3	10 YR 4/3	Silt Loam	Gravels	Many
7	162+	C3	-	10 YR 6/3	10 YR 3/3	Silt Loam	Gravels	Few

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	1	F	Sbk	S	Fr	SO	PO			
2	3	VN	Pl	VH	VFi	VS	P			

3	3	C	Sbk	VH	F	VS	VP			
4	2	F-M	Sbk	MH	F	MS	VP			
5	-	-	Sbk	L	VFr	NS	NP			
6	1	F-M	Sbk	SH	Fr	SO	PO			
7	-	-	MA	SH	Fr	S	P			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2												
3					Charcoal	Very Few	Black	Chunks				
4					$CaCO_3$	Few	White	Filaments				
5												
6												
7												

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	VF- F			8.0		15	Disturbed area
2	2	VF – M			8.0		28	Sand lenses, laminated
3	2	VF			8.0		32	
4					8.0		21	
5					8.0		7	
6	1	VF			8.0		18	
7					8.0		22	

GR 9127

Site: GR 9127

Alternate Site Name: Diablo Sand and Gravel

Locus: None.

Specimen Numbers: 18 - 41

GRIC Numbers: 350 - 361

Age of Field(s): Prehistoric

Associated Canal: Unknown. A large canal not found during excavation.

Landform: Holocene Terrace

Feature Number(s): 2

Field Observations:

- Canal found is ephemeral and deep.
- Agricultural field deposits are located to the north toward the river in two trenches where the canal was found.
- Trenches are located in a fallow cotton field, which was harvested at some point during this year.
- Gravel pit being constructed ½ mile to the north of the sampled area.

Table A.13: Soil Description form for GR 9127

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-48	A_p	AS	10 YR 5/3.5	10 YR 3/4	Silty Clay Loam		
2	48-80	A	AW	7.5 YR 5/4	7.5 YR 4/3	Silty Clay Loam		
3	80-143+	C	-	7.5 YR 6/4	7.5 YR 4/4	Clay Loam		

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	M	Sbk - CDY	VH	VFi	VS	VP			
2	3	F-M	Sbk	VH	VFi	VS	VP			
3	0	0	MA	H	Fi	VS	VP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2					$CaCO_3$		white	Filaments				
3												

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	**Size**	**Size**	**Shape**				
1	2	VF - F	VC	DT	8		28	Disturbed modern plow zone.
2	1	VF - F	F	MT	8		29	Prehistoric Field.
3	1	VF			8		30	.

GR 931 (Prehistoric)

Site: GR 931

Alternate Site Name: Fidel Burciaga Homesite

Locus: None.

Specimen Numbers: 836 – 863

GRIC Numbers: 362 – 375

Age of Field(s): Prehistoric

Associated Canal: Check, area is in Sweetwater neighborhood

Landform: Holocene Terrace

Feature Number(s): 83

Comments:

- Prehistoric fields are hard to see, but some irregular segments are present near the possible prehistoric canal (classified as a medium non-thermal pit in notes). No field deposits are present in trenches to the east (Trenches 213 and 214)
- Area is in the Sweetwater neighborhood – cleared of brush, but not evidence for major historic disturbances, Fidel (whose homesite it is) confirms this.
- Near historic GR 931 and will make a nice complement to this field.
- Fields are differentiated from the upper disturbed zone – granular in structure, higher in clay, no color differences, not present or preserved throughout entire trench.

Table A.14: Soil Description Form for GR 931 (Prehistoric)

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-29	A_p	AW	10 YR 5/3	10 YR 3/3	Silt Loam	Gravels	1
2	29-50	A	AI	10 YR 5/3	10 YR 3/3	Silt Loam	Gravels	2
3	50-91	C_1	AS	10 YR 5/3	10 YR 3/3	Sandy Loam	-	-
4	91-160+	C_2	-	10 YR 5/3	10 YR 3/3	Sandy Loam	-	-

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	M	Sbk - Pl	Sh	Fi	SO	PO			
2	3	F	Gr - Sbk	Sh	Fi	SS	SP			
3	0	0	MA	S	Fr	SO	PO			
4	0	0	MA	S	Sr	SO	PO			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1					$CaCO_3$		white	filaments				
2					$CaCO_3$	Many	white	Filaments and nodules				
3					$CaCO_3$	Few	white	filaments				
4												

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	**Size**	**Size**	**Shape**				
1	3	VF					10	Disturbed from neighborhood use.
2	3	VF					18	Prehistoric Field.
3	1	VF					8	
4	1	VF					7	

GR 485 (Lucero A-5)

Site: GR 485

Alternate Site Name: Lucero A-5

Locus: None.

Specimen Numbers: 118 – 165

GRIC Numbers: 376 – 399

Age of Field(s): Two overlying historic field deposits

Associated Canal: Old Stotonick Canal

Landform: Holocene Terrace

Feature Number(s): Top Field – Feature 30; Bottom Field – Feature 31

Comments:

- Three historic channels cut into each other to the west of where I characterized the profile.
- Crew excavated one possible prehistoric channel to the south of characterized area, but entire area classified as historic due to sheer amount of historic canals.
- Confusing soil profile due to the presence of two historic fields.

Table A.15: Soil Description Form for GR 485 (Lucero A-5)

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-51	A_p	AS	7.5 YR 5/3	7.5 YR 3/3	Sandy Loam	Gravels	3
2	51-70	A1	AW	7.5 YR 5/4	7.5 YR 4/4	Sandy Loam	Gravels	3
3	70-93	A2	AS	7.5 YR 5/4	7.5 YR 3/4	Sandy Loam	Gravels	1
4	93-137	Buried Paleosol	CS	7.5 YR 5/3	7.5 YR 3/3	Silt Loam		
5	137-150+	C	-	10 YR 6/4	7.5 YR 4/3	Silt Loam		

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	C	Sbk	H	Fi	SS	MP			
2	2	F	Sbk-Gr	Sh	VFr	NS	NP			
3	2	F	Sbk-Gr	Sh	VFi	SS	SP			
4	3	C	Pr	H	Fi	S	P			

5	0	0	MA	Sh	Fi	NS	NP			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Shape
1												
2												
3												
4												
5									$CaCO_3$		white	filaments

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	3	VF					15	Highly disturbed plow zone
2	2	VF					10	Slightly laminated historic field, very gravelly and sandy, high in coarse fragments.
3	1	VF					12	Higher in clays than upper field, less coarse fragments, but similar to upper field otherwise.

4	1	VF in cracks					12	Buried Paleosol - also seen across the street.
5	0	-					10	

GR 485 (Lucero A-6)

Site: GR 485

Alternate Site Name: Lucero A-6

Locus: BB

Specimen Numbers: 166 - 189

GRIC Numbers: 400 - 411

Age of Field(s): Historic

Associated Canal: Old Stotonick Canal

Landform: Holocene Terrace

Feature Number(s): 32

Comments:

- Located near Lucero A-5, but no paleosol is located here.
- Fields are well defined and direcly under the plow zone to the north of river and present day and historic canals.
- Fields are slightly darker, higher in clays and $CaCO_3$, laminated in structure compared to other horizons
- Fields become less defined as you move to the southern trenches
- Samples were collected in a variety of trenches to get a broad view of what the fields look like.
- Fields are mapped on Southworth’s 1914 maps.

Table A.16: Soil Description form for GR 485 (Lucero A-6)

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-39	A_p	AS	7.5 YR 5/3	7.5 YR 3/3	Silt Loam	Gravels	1
2	39-78	A	AW	7.5 YR 5/3	7.5 YR 2.5/3	Silty Clay	None.	
3	78-140+	CB	-	7.5 YR 6/3	7.5 YR 3/4	Silt Loam	Gravels	2

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	MC	CDY	H	Fi	MS	MP			
2	3	F-M	Sbk-Abk	VH	VFi	VS	VP			
3	1	0	Sbk-MA	H	Fi	SS	SP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2					$CaCO_3$	Many	White	Filaments				
3					$CaCO_3$	Few	White	Filaments				

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	2	VF - F					20	Disturbed modern plow zone.
2	1	VF					29	Historic Field.
3							14	.

GR 522

Site: GR 522

Alternate Site Name: P. Mendivil Homesite

Locus: None.

Specimen Numbers: 12528 - 12553

GRIC Numbers: 412-424

Age of Field(s): Prehistoric

Associated Canal: No large main canal located during sampling.

Landform: Holocene Terrace

Feature Number(s): 1381

Comments:

- Pre-Classic sherds and artifacts associated with the agricultural deposits.
- No historic artifacts found in the vicinity of sampling area.
- Many modern artifacts on the surface, since surface area was located in the front yard of a modern house.
- Prehistoric field deposits were well-defined in some trenches, but not disturbed in other trenches. Sampling was focused in best-preserved areas.
- No canals were found during testing here, but Midvale mapped a canal directly to the north.

Table A.17: Soil Description form for GR 522

	Depth (cm)	**Horizon**	**Boundary**	**Matrix Color**		**Texture**	**Rock Fragments**	
				Dry	**Moist**		**Size**	**Quantity**
1	0-39	A_p	AW	10 YR 5/3	10 YR 3/3	Silt Loam	Gravels	Few
2	39-93	A	AI	10 YR 3/3	10 YR 3/3	Sandy Loam	Gravels	Common
3	93-150+	C	-	7.5 YR 6/4	7.5 YR 4/4	Silt Loam	Gravels	Common

	Structure			**Consistence**				**Mottles**		
	Grade	**Size**	**Shape**	**Dry**	**Moist**	**Stick.**	**Plast.**	**Quantity (%)**	**Size**	**Color (Dry or Moist)**
1	3	VF - F	Sbk	Vh	Fi	VS	VP			
2	2	F	Gr - Sbk	S	VFr	SS	SP			
3	-	-	MA	Sh	Fr	NS	NP			

	Redoximorphic Features				**Concentrations**				**Ped Surface Features**			
	Kind	**Size**	**Color**	**Shape**	**Kind**	**Concentration**	**Color**	**Shape**	**Kind**	**Size**	**Color**	**Shape**
1												
2					$CaCO_3$	few	white	filaments				
3												

	Roots		**Pores**		**pH**	**Efferv.**	**%Clay**	**Miscellaneous Notes**
	Qty.	**Size**	**Size**	**Shape**				
1	1	M - F- VF			7.5	ST	22	Disturbed, modern plow zone.
2	1	M - F - VF			8	VE	10	Very fine sand, parting to silts. Prehistoric Field Horizon.
3					8	ST	8	.

GR 485 (Homesite)

Site: GR 485

Alternate Site Name: L. White Homesite

Locus: UU

Specimen Numbers: 325-348

GRIC Numbers: 425-436

Age of Field(s): Historic

Associated Canal: No large main canal located during sampling, but smaller historic canals and a reservoir were found during sampling.

Landform: Holocene Terrace

Feature Number(s): 33

Comments:

- Sampling area located in the front yard of the house, so modern disturbance not associated with agriculture.
- Area of protohistoric occupation, so may represent early historic agricultural fields.
- 1952 USGS map has a historic map plotted in this region, but this canal was not located during sampling.

Table A.18: Soil Description form for GR 485 (Homesite)

	Depth (cm)	Horizon	Boundary	Matrix Color		Texture	Rock Fragments	
				Dry	Moist		Size	Quantity
1	0-38	A_p	AS	10 YR 5/3	10 YR 4/3	Silt Loam	None	None
2	38-81	A	GW	10 YR 6/3	10 YR 3/3	Silt Loam	None	None
3	81-132+	C	-	10 YR 7/4	10 YR 4/4	Silt Loam	None	None

	Structure			Consistence				Mottles		
	Grade	Size	Shape	Dry	Moist	Stick.	Plast.	Quantity (%)	Size	Color (Dry or Moist)
1	3	F	Gr - Pl	SH	Fr	SS	SP			
2	3	M	Sbk	H	Fi	S	VP			
3	-	-	MA	SH	Fr	SS	P			

	Redoximorphic Features				Concentrations				Ped Surface Features			
	Kind	Size	Color	Shape	Kind	Concentration	Color	Shape	Kind	Size	Color	Shape
1					$CaCO_3$	many	White	specks				
2												
3					$CaCO_3$	Few	white	filaments				

	Roots		Pores		pH	Efferv.	%Clay	Miscellaneous Notes
	Qty.	Size	Size	Shape				
1	2	F- VF			8	VE	12	Disturbed, modern plow zone.
2	1	F			8	ST	22	Historic Field.
3					8	ST	9	.

APPENDIX B

SAMPLING SITE DESCRIPTIONS FOR THE PAMPA DE CHAPARRI

The following pages provide the soil characteristics and field descriptions of sampling sites on the Pampa de Chaparrí. Because soils were collected as a pilot project for this dissertation, the data collection and tables are different from those used on the middle Gila River (Appendix A). After data collection and analysis of the samples collected on the Pampa, the form used for the middle Gila River was modified and refined in order to accurately address the research question of interest. Profiles of the

Area 1: Well-Preserved Fields

Geomorphic Context: Qru1 – Young Alluvial Fan Surface

Why Sampled: Fields were well-preserved.

Comments:

- Fields are contoured around the topography of the area, unlike other fields on the Pampa.

Table B.1: Soil Characteristics for Area 1

	Depth (cm)	Horizon	Boundary	Roots	Structure		
					Grade	Size	Shape
1	0-23	A	GS	3VF	2	VF	Sbk
2	23-39	Bw	AS	2VF	1	M	Sbk
3	39+	C	-				Loose

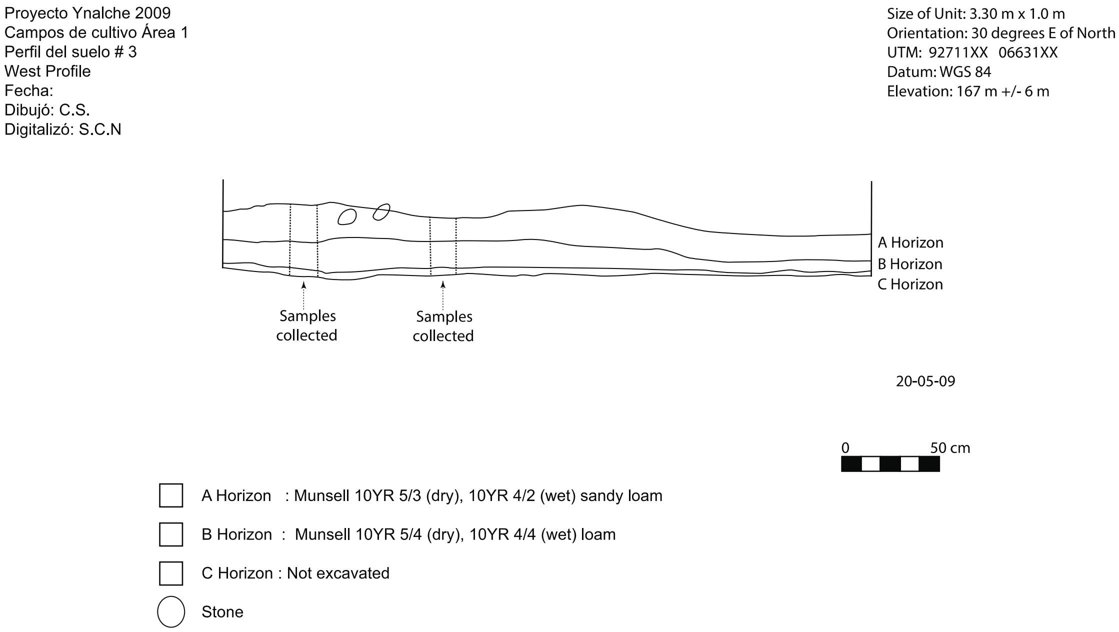


Figure B.1: Profile Map of Area 1

Area 2: Well-Preserved Fields

Geomorphic Context: Qru1 – Young Alluvial Fan Surface

Why Sampled: Fields are well-preserved.

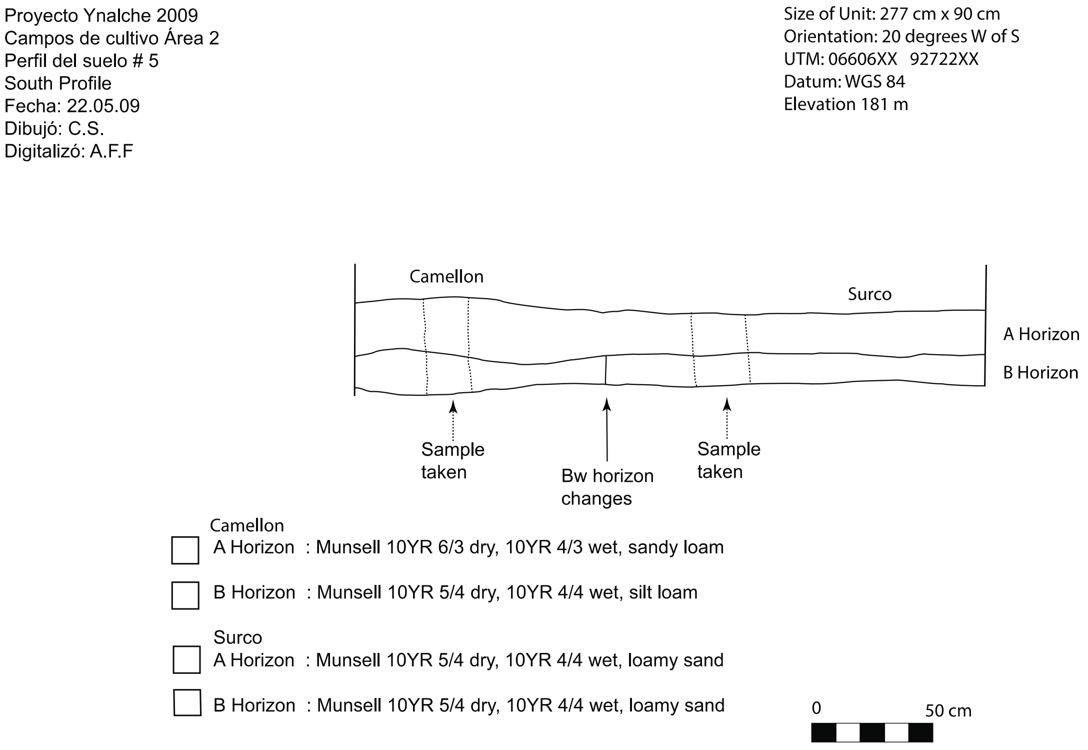
Comments:

- Fields are contoured around the topography of the area, unlike other fields on the Pampa.
- Field canals oriented at 290 degrees**.**
- Ridges and furrows oriented at 195-205 degrees.
- Field canals are 23 meters apart, fields in between.
- Furrows – 1.2 m width

- Ridges – 1 m width
- Dry grasses in furrows, no vegetation on ridges.

Table B.2: Soil Characteristics for Area 2

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-27	A	GS	3VF	2	M	Sbk
2	27-40	Bw	AS	2VF	2	M	Sbk
3	40+	C	-				Loose



Proyecto Ynalche 2009
Campos de cultivo Área 2
Perfil del suelo # 5
South Profile
Fecha: 22.05.09
Dibujó: C.S.
Digitalizó: A.F.F

Size of Unit: 277 cm x 90 cm
Orientation: 20 degrees W of S
UTM: 06606XX 92722XX
Datum: WGS 84
Elevation 181 m

Camellon
☐ A Horizon : Munsell 10YR 6/3 dry, 10YR 4/3 wet, sandy loam
☐ B Horizon : Munsell 10YR 5/4 dry, 10YR 4/4 wet, silt loam

Surco
☐ A Horizon : Munsell 10YR 5/4 dry, 10YR 4/4 wet, loamy sand
☐ B Horizon : Munsell 10YR 5/4 dry, 10YR 4/4 wet, loamy sand

Figure B.2: Profile Map of Area 2

Area 3: Walled Field 1

Geomorphic Context: Qru1 – Young Alluvial Fan Surface

Why Sampled: Fields are enclosed by a large adobe wall.

Comments:

- Fields are not as well-preserved as Areas 1 and 2, but visible at the surface.
- Field canals running downslope at 25 degrees.
- Field canals are 19-21 meters apart, fields in between.
- Furrows – 1.1 m width
- Ridges – 1 m width
- Dry grasses in furrows, no vegetation on ridges.

Table B.3: Soil Characteristics for Area 3

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-15	A	GS	3VF	2	F	Gr-Sbk
2	15-26	Bw	AS	2VF	3	M	Sbk
3	26+	C	-				Loose

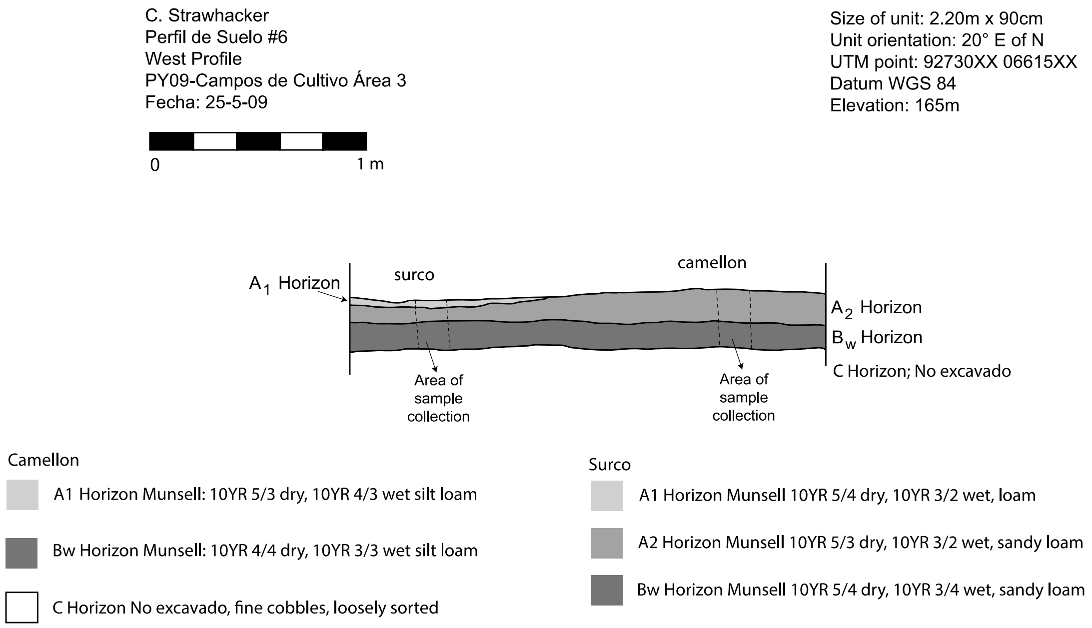


Figure B.3: Profile Map of Area 3

Area 4: Outside of Walled Field 1

Geomorphic Context: Qru1 – Young Alluvial Fan Surface

Why Sampled: Fields are located directly south of the walled fields, so sampled as a comparison to Area 3.

Comments:

- Fields are north of the major RIIB canal.
- Not as well preserved as Areas 1 and 2.
- Field canals running north downslope at 30 degrees.
- Fields are E or comb-shaped.
- Field canals are 27-31 meters apart, fields in between.

- Furrows – 1.0 m width
- Ridges – 1.4 m width
- Furrows highly visible due to color change of soil surface.

Table B.4: Soil Characteristics for Area 4

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-10	A	GS	1VF	2	M	Pl-Sbk
2	10-20	Bw1	GS	1VF	3	M	Sbk
3	20-32	Bw2	-	1VF	3	M	Sbk

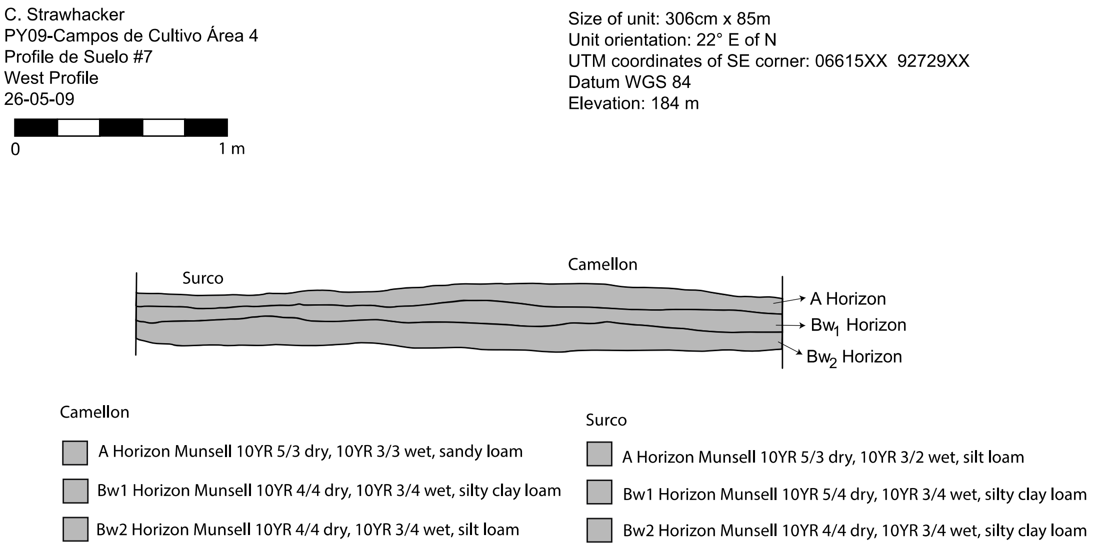


Figure B.4: Profile Map of Area 4

Area 5: Outside of Walled Field 1

Geomorphic Context: Qru1 – Young Alluvial Fan Surface

Why Sampled: Fields are located directly south of the walled fields, so sampled as a comparison to Area 3.

Comments:

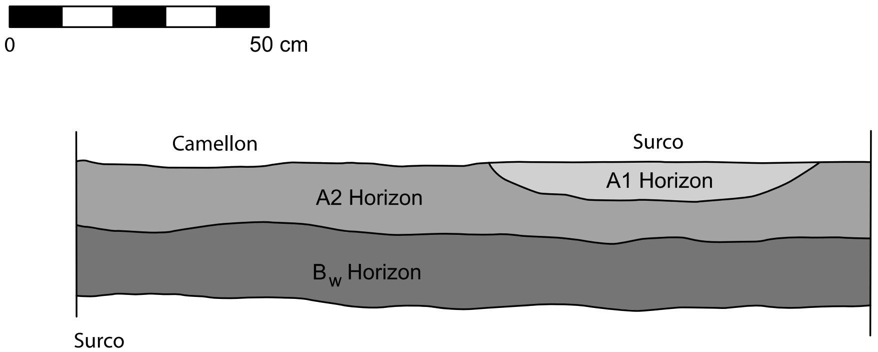
- Fields are north of the major RIIB canal.
- Not as well preserved as Areas 1 and 2.
- Field canals running north downslope at 25 degrees.
- Fields are E or comb-shaped.
- Field canals are 12-13 meters apart, fields in between.
- Furrows – 0.8 m width
- Ridges – 0.7 m width
- Furrows highly visible due to color change of soil surface.

Table B.5: Soil Characteristics for Area 5

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-17	A	GW	2VF	3	M	Sbk
2	17-27	Bw	AS	1VF	2	M	Sbk
3	27+	C	-				Loose

Proyecto Ynalche
C. Strawhacker
Campos de Cultivo Área 5
Profile de Suelo #8
West Profile
Fecha: 28-05-09

Size of unit: 87 cm x 153 cm
Unit orientation: 8° E of N
UTM cooridnates of SE corner: 92729XX 06614XX
Datum WGS 84
Elevation: 158 m



Surco
░ A1 Horizon: Munsell 10YR 5/4 dry, 10YR 3/3 wet, loam

▒ A2 Horizon: Munsell 10YR 5/3 dry, 10YR 3/3 wet, silt loam

▓ Bw Horizon: Munsell 10YR 5/4 dry, 10YR 3/4 wet, silty clay loam
Camellon
▒ A2 Horizon: Munsell 10YR 5/3 dry, 10YR 3/3 wet, silt loam

▓ Bw Horizon: Munsell 10YR 5/4 dry, 10YR 3/4 wet, silt loam

Figure B.5: Profile Map of Area 5

Area 6: Well-Preserved Fields

Geomorphic Context: Dissected Alluvial Fan

Why Sampled: Fields are well preserved and on another part of the Pampa.

Comments:

- Furrows are running parallel to field canals.
- Field canals running 20 degrees east of south.
- Fields are E or comb-shaped.
- Field canals are 16-18 meters apart, fields in between.

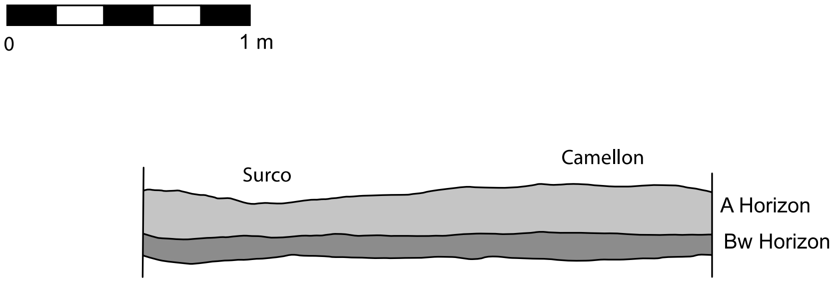
- Furrows – 1 m width
- Ridges – 1.2 m width
- Vegetation differences among ridges and furrows are not distinct, but height differences remain on the surface.

Table B.6: Soil Characteristics for Area 6

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-20	A	AS	3VF- F	1	M	Sbk
2	20-31	Bw	AS	2VF	1	F	Sbk
3	31+	C	-				Loose

Proyecto Ynalche
C. Strawhacker
Campos de Cultivo Área 6
Perfil de Suelo #9
South Profile
Fecha: 01-06-09

Size of unit: 230 cm x 85 cm
Orientation of unit: 70° W of S
UTM point of unit: 92748XX 06570XX ± 4 m
Datum: WGS 84
Elevation: 149 m



Camellon

░ A Horizon: Munsell 10YR 5/3 dry, 10YR 3/3 wet, silt loam

▓ Bw Horizon: Munsell 7.5YR 4/4 dry, 10YR 4/4 wet, silt loam

Surco

░ A Horizon: Munsell 10YR 5/3 dry, 10YR 3/3 wet, loam

▓ Bw Horizon: Munsell 7.5YR 4/6 dry, 7.5YR 4/6 wet, sandy loam

Figure B.6: Profile Map of Area 6

Area 7: Well-Preserved Fields

Geomorphic Context: Dissected Alluvial Fan Surface.

Why Sampled: Fields are well preserved and on another part of the Pampa.

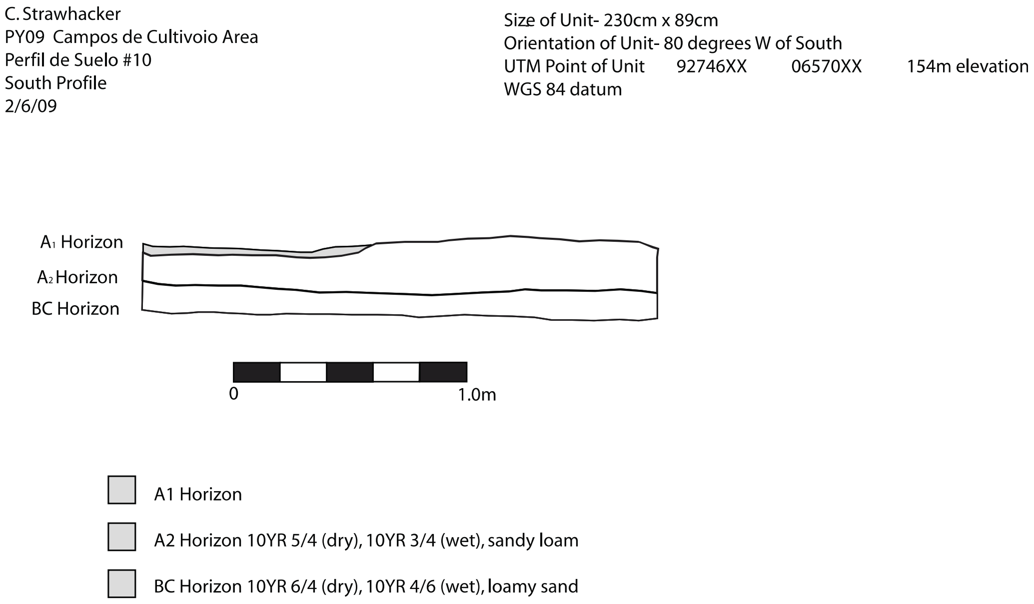
Comments:

- Located close to a large distributory canal.
- Located to the south of Area 6.
- Field canals running 25 east of south.
- Fields are E or comb-shaped.

- Field canals are 18-20 meters apart, fields in between.
- Furrows – 1.1 m width
- Ridges – 1.3 m width
- Ridges and furrows run perpendicular to field canals.
- Furrows highly visible due to color change of soil surface.

Table B.7: Soil Characteristics for Area 7

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-24	A	GS	3VF-F	2	M	Gr-Sbk
2	24-35	BC	AS	2VF-F	1	M	Sbk
3	35+	C	-				Loose



C. Strawhacker
PY09 Campos de Cultivoio Area
Perfil de Suelo #10
South Profile
2/6/09

Size of Unit- 230cm x 89cm
Orientation of Unit- 80 degrees W of South
UTM Point of Unit 92746XX 06570XX 154m elevation
WGS 84 datum

▨ A1 Horizon
▨ A2 Horizon 10YR 5/4 (dry), 10YR 3/4 (wet), sandy loam
▨ BC Horizon 10YR 6/4 (dry), 10YR 4/6 (wet), loamy sand

Figure B.7: Profile Map of Area 7

Area 8: Outside of Walled Field 2

Geomorphic Context: Distal End of Alluvial Fan

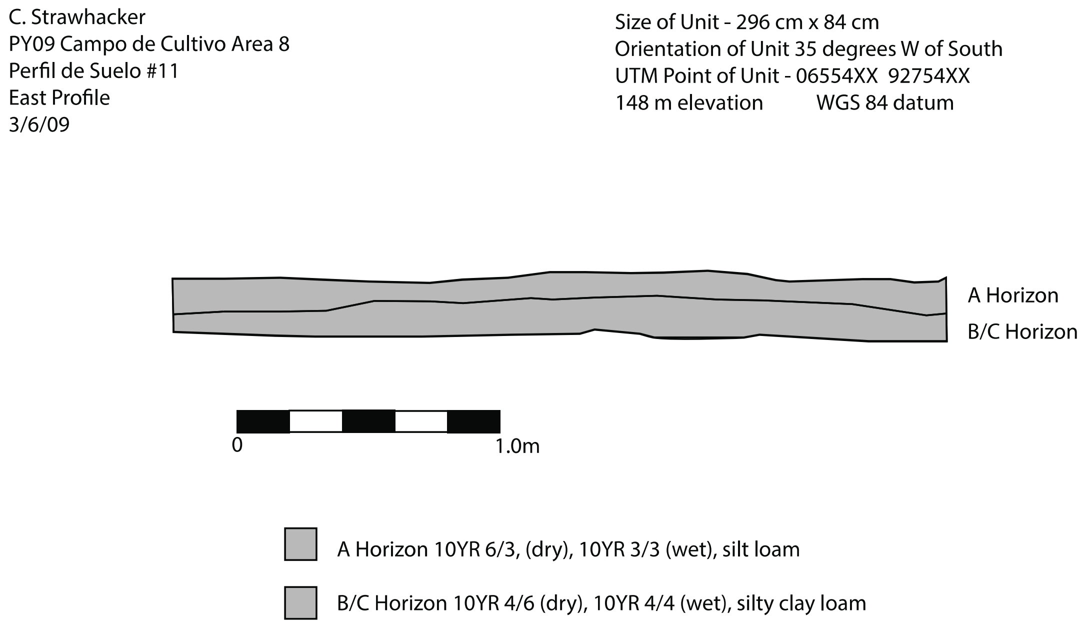
Why Sampled: Fields are located outside of the second walled field, so provide a comparison to soils within the walled field 2.

Comments:

- Surface looks highly deflated, almost like desert pavement.
- Lots of surface artifacts in this field area.
- Field canals running 35 east of north.
- Fields are E or comb-shaped.
- Field canals are 13-16 meters apart, fields in between.
- Furrows – 1.2 m width
- Ridges – 2.6 m width
- Ridges and furrows run perpendicular to field canals.
- There is evidence for an earlier field construction that is structured differently from the fields sampled.

Table B.8: Soil Characteristics for Area 8

	Depth (cm)	Horizon	Boundary	Roots	Structure		
					Grade	Size	Shape
1	0-12	A	AS	2VF	3	M	Sbk
2	12-21	BC	AS	1VF	2	M	Sbk
3	21+	C	-				Loose


C. Strawhacker
PY09 Campo de Cultivo Area 8
Perfil de Suelo #11
East Profile
3/6/09

Size of Unit - 296 cm x 84 cm
Orientation of Unit 35 degrees W of South
UTM Point of Unit - 06554XX 92754XX
148 m elevation WGS 84 datum

Figure B.8: Profile Map of Area 8

Area 9: Waffle Gardens

Geomorphic Context: Distal End of Alluvial Fan

Why Sampled: Fields are unique among other fields found on the surface of the Pampa.

Comments:

- Located close to the large RIIC distributory canal.
- Located close to a very large adobe site.

- Field canals running 35 east of north.
- Fields are waffle shaped.
- Field canals are alternating at17-18 meters apart, and then 28-31 meters apart fields in between.
- Furrows – 1.1 m width
- Ridges – 1.6 m width
- Ridges and furrows run parallel to field canals.
- Furrows highly visible due to height differences between ridges and furrows.

Table B.9: Soil Characteristics for Area 9

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-8	A	AS	3VF, 1 M	3	M	Gr-Sbk
2	8-18	Bw1	GS	2VF	3	M	Sbk
3	18-28+	Bw2	-	1VF	3	M	Sbk

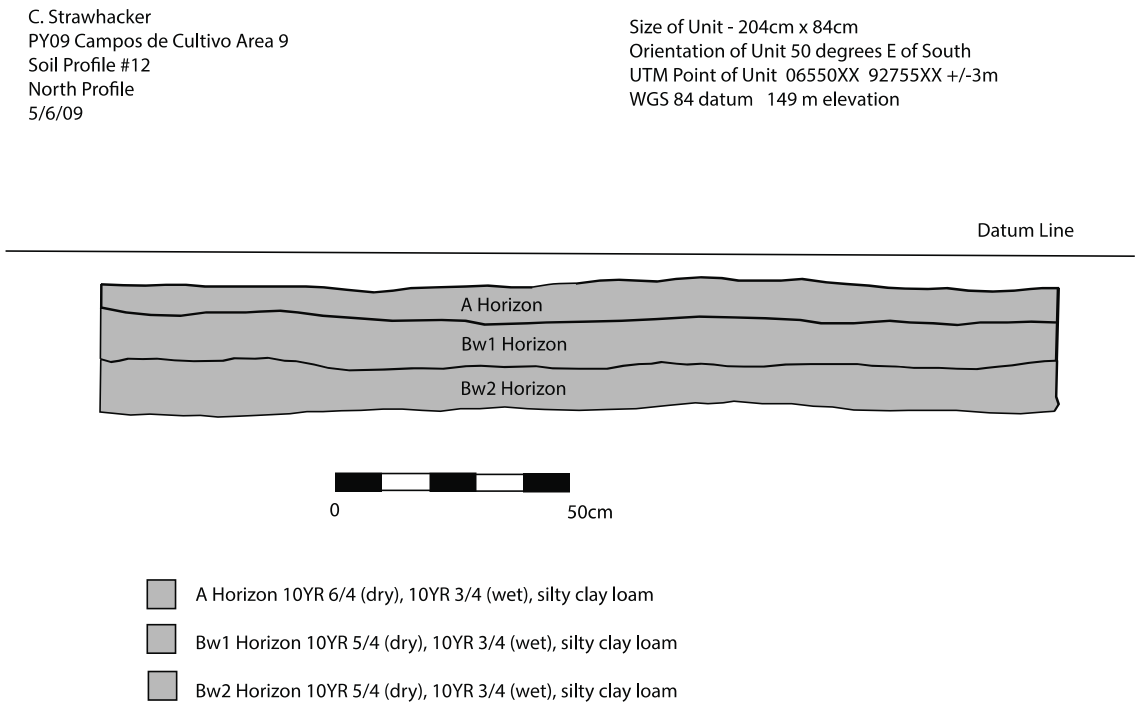


Figure B.9: Profile Map of Area 9

Area 10: Walled Field 2

Geomorphic Context: Distal End of Alluvial Fan

Why Sampled: Fields are located within a second large adobe wall.

Comments:

- Large canal running directly in the center of the entire walled area.
- Field canals running 45 west of north.
- Fields are highly eroded, but still visible on the surface.
- Fields are comb-shaped.
- Field canals are alternating at 18-34 meters apart with fields in between.
- Furrows – 1.5 m width

- Ridges – 1.2 m width
- Ridges and furrows run perpendicular and upslope to field canals.
- No real height differences between ridges and furrows.

Table B.10: Soil Characteristics for Area 10

	Depth (cm)	Horizon	Boundary	Roots	Structure		
					Grade	Size	Shape
1	0-10	A	AS	2VF	2	M	Gr-Sbk
2	10-20+	Bw	-	2VF	3	M	Sbk

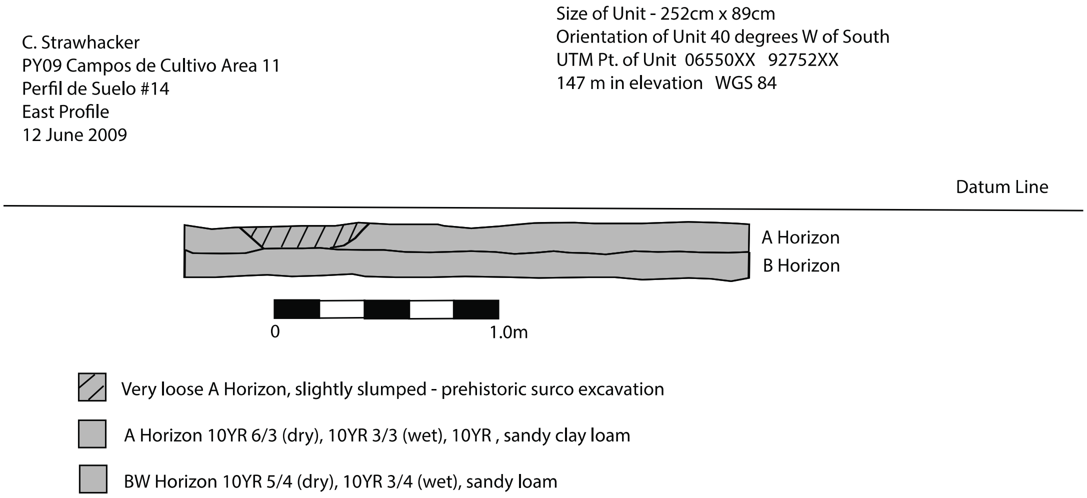


Figure B.10: Profile Map of Area 10

Area 11: Sicán Fields

Geomorphic Context: Qrl2 (see Huckleberry et al. 2012)

Why Sampled: Fields were abandoned during the Sicán Period, making them the earliest abandoned fields on the Pampa.

Comments:

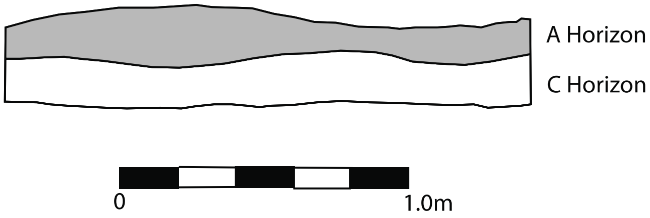
- Vegetation is dense in this part of the Pampa.
- Field canals running 35 west of north.
- Fields are still visible on the surface.
- Field canals are alternating at 13-15 meters apart with fields in between.
- Furrows – .85 m width
- Ridges – .90 m width
- Ridges and furrows run perpendicular and upslope to field canals.

Table B.11: Soil Characteristics for Area 11

	Depth (cm)	**Horizon**	**Boundary**	**Roots**	**Structure**		
					Grade	**Size**	**Shape**
1	0-22	A	AW	2VF	2	F	Gr-Sbk
2	22+	C	-	3VF	0		Loose

C. Strawhacker
PY09 Campos de Cultivo Area 11
Perfil de Suelo # 13
NE Profile
9 June 2009

Size of Unit: 183 cm x 80 cm
Orientation of Unit 40 degrees E of South
UTM Point of Unit: 06631XX 92698XX
197m elevation



▨ A Horizon 10YR 6/4 (dry), 10YR 3/4 (wet), sandy loam

☐ C Horizon 10YR 5/4 (dry), 10YR 4/4 (wet), sand

Figure B.11: Profile Map of Area 11

APPENDIX C

EVALUATION OF OTHER SOIL FORMATION DRIVERS ON THE MIDDLE GILA RIVER

The challenges for sampling and comparing prehistoric and historic fields on the middle Gila River include the numerous natural and anthropogenic factors driving soil formation processes, and the physical and chemical characteristics of the soil. In order to isolate the driving issue of interest for this analysis – prehistoric and historic irrigation agriculture – other factors, such as geomorphology and the presence of a modern agricultural field, need to the evaluated in how they may affect soil characteristics in prehistoric and historic agricultural fields.

Not surprisingly, geomorphology is the main, natural driving force affecting soil formation processes along the middle Gila River. As seen in the results presented in Chapter 6 (Figures 6.1 a-k), many of the soil characteristics are driven largely by the age of the geomorphic surface – either Pleistocene Holocene -- including sodicity, salinity, the presence of argillic horizons, and soil texture. The Pleistocene Terrace was formed sometime before 18,000 B.P. and has distinct morphology due to its age compared to the Holocene Terrace, which has sediments that date from 18,000 B.P. to present (Waters and Ravesloot 2001). Soils on the Pleistocene Terrace are well-developed due to illuviation of clays through the soil profile, creating B horizons high in clay, which are frequently absent from soils on the Holocene Terrace. Much of the Pleistocene Terrace has also been covered by an eolian sand sheet, which Haury (1976) and Waters and Ravesloot (2001) have argued would have been ideal for cultivation (Figure 3.1). Because of the variability in soil characteristics based on geomorphology, it is important to compare prehistoric and historic fields within the same geomorphic context to ensure the soil variables are reflecting signatures of prehistoric and historic behavior.

The GRIC also has many modern agricultural fields that are cultivated on top of these ancient agricultural sediments. With the further addition of irrigation water and fertilizer and multiple mechanical plowing episodes, it is possible that, like pollen, physical and chemical soil characteristics of the buried prehistoric and historic fields could be affected by modern agriculture. Of particular interest were levels of total Nitrogen, since nutrients from added fertilizers may infiltrate down to prehistoric or historic field strata and thus artificially elevate levels of Nitrogen in those contexts.

Figure C.1 shows the amounts of Total Nitrogen (g N / kg soil) in different field contexts and their relationship to modern agricultural fields. While the ancient agricultural fields are higher than the control samples in Total Nitrogen – a result discussed in the following sections - the overall differences in Total Nitrogen between sampled areas that are under a modern field and those that are not are not statistically significant. Interestingly, the soils from prehistoric and historic agricultural fields do not appear to be affected by the presence of a modern agricultural field.

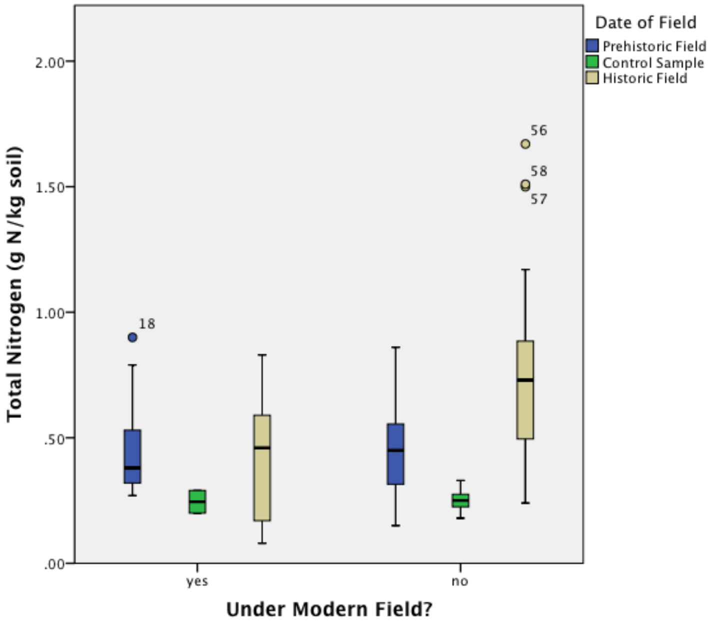


Figure C.1: Levels of Total Nitrogen of Sampling Contexts and Their Presence to a Modern Field

These results indicate that, not surprisingly, many aspects of the GRIC natural and anthropogenic landscape are affecting the formation of the soil profile and the physical and chemical characteristics of the soil, including geomorphology and, in the following sections, ancient irrigation agriculture. Fortunately, the methods established here for the identification and sampling of these ancient agricultural fields can control for these complicating factors to isolate the impacts of long-term irrigation in both the prehistoric and historic periods on soil quality.