The Ancient Agroecology of Perry Mesa:

Integrating Runoff, Nutrients, and Climate

by

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ABSTRACT

Understanding agricultural land use requires the integration of natural factors, such as climate and nutrients, as well as human factors, such as agricultural intensification. Employing an agroecological framework, I use the Perry Mesa landscape, located in central Arizona, as a case study to explore the intersection of these factors to investigate prehistoric agriculture from A.D. 1275-1450. Ancient Perry Mesa farmers used a runoff agricultural strategy and constructed extensive alignments, or terraces, on gentle hillslopes to slow and capture nutrient rich surface runoff generated from intense rainfall. I investigate how the construction of agricultural terraces altered key parameters (water and nutrients) necessary for successful agriculture in this arid region. Building upon past work focused on agricultural terraces in general, I gathered empirical data pertaining to nutrient renewal and water retention from one ancient runoff field. I developed a long-term model of maize growth and soil nutrient dynamics parameterized using nutrient analyses of runoff collected from the sample prehistoric field. This model resulted in an estimate of ideal field use and fallow periods for maintaining long-term soil fertility under different climatic regimes. The results of the model were integrated with estimates of prehistoric population distribution and geographical characterizations of the arable lands to evaluate the places and periods when sufficient arable land was available for the type of cropping and fallowing systems suggested by the model (given the known climatic trends and land use requirements). Results indicate that not only do dry climatic periods put stress on crops due to reduced precipitation but that a reduction in expected runoff events results in a reduction in the amount of nutrient renewal due to fewer runoff events. This reduction lengthens estimated fallow cycles, and probably would have

increased the amount of land necessary to maintain sustainable agricultural production. While the overall Perry Mesa area was not limited in terms of arable land, this analysis demonstrates the likely presence of arable land pressures in the immediate vicinity of some communities. Anthropological understandings of agricultural land use combined with ecological tools for investigating nutrient dynamics provides a comprehensive understanding of ancient land use in arid regions.

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Chapter 1:

INTRODUCTION

The Perry Mesa region, which was intensively occupied from A.D. 1275-1450, is the location of several dozen medium and large masonry pueblos surrounded by extensive agricultural alignments, or terraces. Ancient Perry Mesa farmers constructed terraces on gentle hillslopes to slow and capture nutrient rich surface runoff generated from intense rainfall. On the one hand, the widespread distribution of these agricultural features may indicate that farming was difficult for Perry Mesa residents and required extensive intensification efforts. On the other hand, the widespread distribution of these features may speak to the productivity of the agricultural landscape and indicate how easily it was exploited for food production. The truth is likely more complex than this dichotomy and understanding the function of extensive terraces is important for understanding the Perry Mesa land use strategy and the agricultural capacity of the region.

In the North American Southwest, studies that have reconstructed agricultural capacity and yields are generally contingent upon identification of naturally occurring wet and dry climatic periods and natural soil moisture retention (e.g., Benson 2009; Ingram 2013; Van West 1994; Van West and Altschul 1994, 1997) rather than incorporating the role of intensification efforts in improving agricultural capacity. Water is one of the main limiting factors to primary production in agroecosystems (Gliessman 2007) and is thought to be the most limiting factor in arid and semi-arid ecosystems in general (Ludwig 1987). Therefore, fluctuations in the availability of water due to changing climate can greatly influence agricultural outcomes.

A focus on water alone, however, minimizes the influence of another important factor of agricultural production – nutrients– and the focus on naturally occurring water minimizes the influence of human manipulation of the landscape to improve moisture conditions. Nutrients are important for crop yield, size, and resistance to disease and pests, and nutritional deficiencies can reduce the capacity to adjust to water and temperature stresses (Muenchrath and Salvador 1995). After water, nitrogen (N) and phosphorus (P) are the secondarily limiting factors to plant growth in arid and semi-arid ecosystems (Hooper and Johnson 1999). Nutrient declines as a result of farming and nutrient renewal from fallowing and incorporation of runoff, are less frequently incorporated into yield and arable land estimates (although see examples from Benson 2010a, 2010b; Kohler et al. 2007; Schollmeyer 2009). Nutrient dynamics, however, are an important component of understanding Southwestern acroecosystems (Sandor et al. 2007). Many of the strategies used to increase water availability to agricultural fields also can enhance the availability of nutrients. There are many locations in the Southwest, such as washes, hillslopes, and valley margins, which receive considerable amounts of water due to runoff generated during and after intense storms. This runoff contains sediments and organic debris that has been put into suspension by the runoff flow. Farmers in the Southwest chose these locations and improved the benefits of runoff through the construction of landscape modifications including terraces.

In order to investigate the extent to which runoff could have enhanced crop nutrient availability and influenced agricultural capacity, I conducted a series of field and laboratory analyses in prehistoric agricultural fields in the Perry Mesa region of central Arizona. The relatively short duration of the prehistoric occupation and the density of ancient runoff agricultural terraces make it an ideal place to investigate the dynamics of soil fertility as related to agriculture. The setting also differs topographically from locations where similar studies have occurred, such as the *ak-chin,* or arroyo mouth, field locations of contemporary Tohono O'odham (Nabhan 1984, 1986) and the valley margin fields presently farmed by the Zuni (Norton et al. 2001, 2007a; Sandor et al. 2002, 2007). Perry Mesa is an upland mesa, covered with gentle rolling hills that generate small-scale runoff events. It lacks the organic-rich upland catchments of O'odham *ak-chins* and Zuni valley bottom fields. Many prehistoric landscapes in the Southwest, however, are like Perry Mesa and are located in upland areas. Thus, using the Perry Mesa case study, we can further develop our understanding of how runoff nutrient dynamics influence the sustainability of agricultural production across much of the Southwestern landscape.

Dissertation Objectives

In this dissertation, I focus on four research objectives described below. Chapter 2 presents the agroecological framework underlying the principals of nutrient and water dynamics discussed throughout the dissertation. Chapter 3 provides an overview of the prehistoric context of the Perry Mesa.

1. *Characterization of runoff agroecosystems on Perry Mesa.* Several analyses were conducted to characterize the agroecosystems present on Perry Mesa. Most included a comparison of modified agricultural terraced areas with environmentally similar but unmodified locations that were presumably uncultivated or cultivated less intensively. The comparison allows for an assessment of the degree to which landscape modification alters water retention and soil nutrient renewal. A series of trenches were excavated within

the Bull Tank Agricultural Field, a large agricultural terrace system in the northwest portion of Perry Mesa, which provided information about the soil conditions in typical runoff fields (Chapter 4). Runoff was collected and nutrient content analyzed to determine the quantity and quality of runoff on the mesa (Chapter 6). Long-term, in-situ soil moisture monitoring provided information about how soil moisture fluctuated throughout the seasons, was influenced by the presence of agricultural terraces, and influenced prehistoric agricultural productivity (Chapter 5).

2. *Simulation model of long-term maize agriculture and soil nutrient dynamics*. The nutrient data acquired through the analyses mentioned above, together with estimates of nutrient removal by maize plants, available nutrient pools, and rainfall were used to parameterize a simulation model of long-term nutrient dynamics. The model, including the source and values of model variables, is discussed in Chapter 7. This type of modeling approach does not attempt to simulate specific annual yields but rather focuses on the conditions that influence soil fertility over time. Results of the simulation were used to estimate the number of agricultural seasons a field could be farmed before nutrient levels would be less than maize requirements, as well as the number of seasons necessary to replenish nutrients to precultivation levels. The simulation model considered maize cultivation under dryland conditions (no runoff was considered) and runoff conditions. The model was used to estimate crop-to-fallow periods under wet, average, and dry climatic conditions.

3. *Characterization of agricultural land distribution and land use requirements*.

Several analyses were completed to characterize the distribution of potentially arable land within the Perry Mesa region, the density of population during the height of regional population in the late 13th through the 15th centuries, and the amounts of agricultural land required for the population on Perry Mesa (Chapter 8). Chapter 8 also presents an evaluation of when and where agricultural land surpluses and shortages may have occurred.

4. *Evaluation of the relationship between agricultural productivity and settlement dynamics on Perry Mesa*.

This evaluation integrates the previous objectives to address the question of whether, even in the face of potential soil depletion, there was sufficient arable land in the Perry Mesa region for long-term occupation and how the distribution and amount of potentially arable land may have influenced the settlement pattern of the region (Chapter 8). Given the considerable area that Perry Mesa residents terraced, it is possible that there was sufficient agricultural land for people to open new areas to cultivation as farmed ones became depleted. This evaluation integrates reconstructed climatic information to discuss periods of possible arable land excess and shortages based up on the fallowing system suggested by the nutrient renewal rates used in the simulation model. The analysis also integrates a GIS model of potentially arable land to discuss where these arable land stresses may have occurred. Implications for the settlement pattern, including hypotheses testable with future data, are discussed.

Integration of all components of this research is necessary to fully comprehend the agricultural sustainability and capacity of the Perry Mesa agroecosystem. This dissertation was developed from an ecological understanding of agroecology and an archaeological understanding of land use. While the case study focuses on the 13th and 14th century occupation of Perry Mesa in central Arizona, it also contributes to the understanding of ancient runoff agricultural systems throughout the greater Southwestern region and is relevant to addressing the long-term sustainability of contemporary small-scale agriculture in water-limited agroecosystems globally.

Using a combination of archaeological evidence, field and laboratory analysis, mathematical modeling, and GIS, I assessed the agroecological system of the Perry Mesa region. I conclude that surface runoff was important in bringing nutrients and water to fields, ultimately renewing fertility. Terraces improved runoff conditions. However, fallowing was still necessary to offset the nutrients extracted through farming activities, and thus, more agricultural land was required per person required to maintain fertility in this agroecosystem than was likely farmed in a season. Climate influenced the frequency and intensity of runoff producing events and ultimately, therefore, the rate of nutrient renewal and fallow lengths. While the overall Perry Mesa area was not limited in terms of arable land, this analysis demonstrates the likely presence of arable land pressures in the immediate vicinity of some communities. It is concluded that the abundance of agricultural terraces and small field house structures in the region is a result of the need to exploit runoff and maintain extensive agricultural land.

Chapter 2:

AGROECOLOGY, RUNOFF AGRICULTURAL SYSTEMS, AND NUTRIENTS

The primary goal of this chapter is to explain the agroecosystem framework used in this dissertation and to discuss important agroecosystem components, particularly nutrients, in relation to the environmental and cultural context of the prehistoric American Southwest. The focus is on runoff agricultural systems, defined below, the dominant agricultural strategy used in the Perry Mesa region, the case study for this analysis.

According to Stephen Gliessman (2007:18), agroecology is the "application of ecological concepts and principles to the design and management of sustainable food systems." Agroecology takes a whole-system approach with an ecological basis to explain the functioning of agricultural management strategies over the long term (Gliessman 2007). The focus is on sets of inputs and outputs and the interconnections of their component parts at different spatial scales – from individual plants to the field or the ecosystem level. The concern is with the health of the entire system rather than the viability of a specific crop species.

Agroecology differs from agronomic frameworks in the sense that agronomy focuses on the management of biogeochemical processes of the system that relate to crop use, particularly those that maximize crop yield, whereas agroecology focuses on all biogeochemical process of the entire ecosystem (Drinkwater 2004). Within the ecosystems approach of agroecology, fertility is maintained by balancing nutrient additions and exports through optimizing nutrient cycling within the soil as opposed to maintaining fertility through external nutrient additions such as nitrogen and phosphorus fertilizers. Natural nutrient cycling is maximized in ecosystem approaches with the use of organic residues, biological nutrient fixation, maintenance of cover crops, and/or the use of diversified plant species and management strategies (Drinkwater 2004).

Agroecology not only integrates the ecological perspectives of agricultural systems but includes social, economic, and political perspectives as well. Socio-economic factors are important and regulate the energy inputs and outputs of the entire food system (Francis et al. 2003; Gliessman 2007). Therefore, an agroecosystem approach more appropriately characterizes how small-scale traditional farmers manage agronomic resources. While crop, soil, and water interactions are foundational to the function of agroecosystems, so are the decision-making processes of farmers, which are structured by socio-economic institutions. Agroecology focuses on adapting the selection of plants that are cultivated to the local ecological conditions rather than adapting the entire farm and management system to a particular crop variety. This philosophy is more in line with traditional agricultural systems.

Runoff Agricultural Systems

Understanding locally adapted strategies and technologies is critical to exploring crop cultivation from an agroecosystem perspective. This dissertation, and specifically the discussion of agroecosystems in this chapter, draws on the vast archaeological, ethnographic, and historic literature about agricultural land use in the American Southwest. For geographic reference, the locations of historic and contemporary groups in the American Southwest are shown in Figure 2.1 and groups mentioned from other areas of the world are described in the text.

The focus of this study is on runoff agroecosystems, a type of dryland farming where fields are placed in areas that intercept surface runoff flows. Dryland farming is a form of crop production in semi-arid regions of the world where cropping season rainfall does not meet the needs of the crop, irrigation is not possible, and thus water harvesting and conservation techniques are necessary (Gliessman 2007). Capture of runoff is one way to supplement rainfall. Runoff agricultural strategies integrate field placement, soil characteristics, and landscape modification to maximize the available moisture for crops by concentrating direct precipitation as well as tapping into natural watershed and ecohydrological processes by controlling runoff (Sandor 1995; Sandor et al. 2007). Runoff agriculture has a deep history and is currently practiced in many arid and semi-arid regions in Africa, the Near East, central Asia, and the Americas (Barrow 1990; Bigas et al. 2009; Donkin 1979; Doolittle 2000).

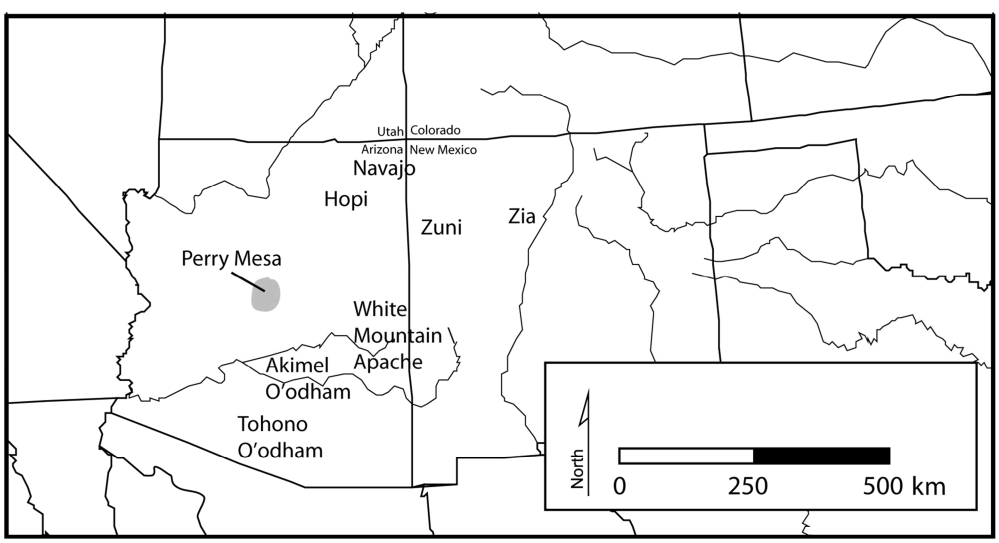


Figure 2.1. Location of cultural groups discussed in the text.

Summer precipitation in the American Southwest is characterized by intense, short-lived thunderstorms that frequently produce overland flooding. In addition to water, runoff also carries with it sediment and organic matter. Discussed in more detail below, controlling runoff plays an important role in maintaining the fertility of agricultural fields.

The types of landscape modification used in Southwestern runoff systems range from ephemeral brush alignments or earthen embankments to more complex and permanent systems of stone terraces. Archaeologically it is typically only the modifications constructed out of stone that are visible. Modifications or features used to impede runoff are referred to by a number of names and classification systems in Southwestern archaeological literature (Donkin 1979; Doolittle 2000; Doolittle and Neely 2004; Maxwell and Anschuetz 1992; Wells 2003; Woodburry 1961; Woosley 1980). For purposes here, stone modifications used in runoff agricultural systems are considered terraces (after Doolittle 2000; Sandor 2006), regardless of the fact that they may often be only one or two courses high. Terraces follow natural topographic contours, are perpendicular to the slope, and impede the overland runoff flow by forming a barrier.

Southwestern runoff agricultural fields are typically located at valley margins along footslopes, ephemeral stream terraces, and gentle hillslopes in upland environments (Doolittle 2000; Sandor 1995). This environmental setting is very different than irrigation or floodwater strategies where fields are located in floodplains and valley settings adjacent to permanent or annual water courses. Field slopes are gentle, usually ranging from 1-7 %, providing enough slope to generate surface runoff but minimal threat of damage from high velocity flows. Use of contour terraces of stone or brush also aids in reducing flow velocity to prevent erosion and retains the moisture within the system. Drainage areas in runoff agricultural systems are relatively small, usually 5-200 ha. Systems of this size have a low probability of high magnitude runoff that can wash out fields. Arid regions have an inverse relationship between watershed size and runoff amounts meaning there is a higher frequency of runoff to be produced in smaller watersheds because of the overland flow generated by small, short duration events is diminished before it reaches larger watersheds (Faures 1995; Sandor 1995). The fields themselves also tend to be small, mostly 1-15 ha with a ratio of field to drainage area average of about 1:25, though this relationship can vary widely. Southwestern runoff fields tend to be in locations, or just downslope from areas, with argillic horizons and other slowly permeable layers runoff because of slow infiltration and these types of locations retain water within root zones by preventing downward percolation (summary in Sandor 1995:125).

The runoff agricultural systems just described differ from a harvesting practice known as *ak-chin* farming. *Ak-chin,* an O'odham word for arroyo mouth, describes the location of fields at the base of washes that intermittently flow during summer storms (Nabhan 1983; 1986). Crops are planted where the slope flattens into an alluvial fan where water, sediments, and organic debris are deposited. The primary difference between runoff farming as discussed here and *ak chin* farming is the specific geomorphologic context of field placement. Similar agroecosystem benefits of increased water and nutrients, however, occur in both types of systems.

Agroecosystem Components

The components of agroecosystems are complex and include sunlight, carbon dioxide, temperature, water, nutrients, soil structure and texture, germplasm, and farmer management of these variables as well as the environmental context of the system. These components influence crop growth and development such as germination, photosynthesis, pollination, nutrient uptake, and yield.

These components work together synergistically such that their effects can cascade throughout the system and either have an immediate or delayed influence on one another. Because of the complex interactions within agroecosystems it is a challenge to predict the consequences of changing a particular variable state (Gliessman 2007).

Nutrients

The analysis presented in this dissertation focuses on the availability and cycling of nutrients within a runoff agroecosystem in the prehistoric Southwest. Nutrients are an important factor affecting agricultural productivity, particularly over the long-term. Nutrients affect crop yield, size, and resistance to disease and pests, and deficiencies can reduce the capacity to adjust to water and temperature stresses (Muenchrath and Salvador 1995). Crop performance is highly dependent upon water, and if water is not adequate it does not matter if nutrient needs are met. However, the highest reductions in yield occur when there is a combination of moisture stress and fertility stress (Claassen and Shaw 1970). Water is also important as a nutrient delivery mechanism, moving them though the soil, through roots into the plant.

Maize growth depends upon 13 different elements from the soil; however only a few (nitrogen [N], phosphorus [P], and potassium [K]) are classified as primary nutrients

(Olson and Sander 1988). Nitrogen is regarded as the most limited nutrient for plants in arid environments (Berry 1995; Hooper and Johnson 1999; Ludwig 1987; Moorhead et al. 1986; Sandor et al. 2007). From an agricultural perspective, nitrogen is the most needed but also the most deficient nutrient in many ecosystems (Gliessman 2007:38; Robertson 1997). Consequently sustainable agroecosystems must minimize N loss and maximize N use efficiency. N is a highly transitory nutrient whose concentrations are continually in flux as it cycles between soil, plants, water, and the atmosphere. Therefore, the timing of N availability is highly variable, and its availability can lead to different outcomes depending upon plant growth stage (Gardner et al. 1985; Olson and Sander 1988). Nitrogen is the integral component of amino acids, the building blocks of proteins which are critical for human and animal nutrition (Brady and Weil 2007).

For maize, the presence of adequate N has important implications for yield and susceptibility of plants to stress (Bloom 1997; Uhart and Andrade 1995). Deficiencies of nitrogen lead to chlorosis (yellowing of leaves), stunted growth, loss of disease resistance, smaller kernel and ear size, poor kernel set, and less protein content of grain and overall lower productivity (Bloom 1997; Brady and Weil 2007; Gardner et al. 1985; Olson and Sander 1988; Uhart and Andrade 1995). If there are nitrogen deficits, the available nitrogen is first directed towards root growth to increase the area from which nitrogen can be extracted. If there is additional nitrogen available in the system it is then directed to the growth of plant shoots, and only when there is sufficient nitrogen for shoots is it directed to fruits/grains. This partitioning has implications for grain production (Bloom 1997). If deficits are severe, the plants begin to take nitrogen from themselves and begin to drop leaves and weaken stalks making them susceptible to disease, lodging, and pests (Bloom 1997, Uhart and Andrade 1995). Nitrogen deficiencies also influence yield of other crops.

Nutrient availability is dependent upon the physical properties of soils, such as soil texture and structure. Nitrogen is readily dissolved in soil water and therefore moves by means of mass flow, making it as mobile as water within the soil column. Well-drained soils thus have a greater likelihood of being nitrogen-depleted because nitrogen can travel out of the soil as water drains. Nitrogen, however, is not mobile without water or the ability for water to move within the soil profile. Other nutrients like phosphorus are easily absorbed on the surfaces of soil particles and therefore move more slowly in the soil column (Brady and Weil 2007).

Nutrient Replenishment Sources

Determining the amounts of nutrient necessary for optimal production is one of the most difficult problems for modern agriculture (Olson and Sander 1988) and was likely a major concern for prehistoric farmers as well. Agricultural fields can receive nutrient inputs from numerous sources including external sources (river flooding, surface runoff, dust, fixation from the atmosphere, organic fertilizers, or synthetic fertilizers) or internal sources (N-fixation, mineralization of nutrients from organic material by microbes and rock weathering). One of the primary losses of nutrients within an agricultural field is from the removal of crops that have integrated nutrients into their cells. Other losses of nutrients for the growth of crops can occur through water and as particles (leaching, erosion, and surface runoff), as gases (denitrification, nitrification, and volatilization) as well as growth from weeds or other plants. Farmers manage soil fertility by maximizing nutrient inputs and internal cycling while minimizing nutrient loss.

Agriculture in the Southwest was sustained in some places for centuries without the use of fertilizer or external inputs such as the Zuni River Valley (Sandor et al. 2007) or the Salt River Valley of the Hohokam region (Howard 2006). Practices involving nutrient maintenance and recovery strategies include management of river floodwater and surface runoff, intercropping with nitrogen-fixing plants, use of fallow or crop rotation, and other farmer management activities such as the use of decomposing crop residue and burning of fields.

Management of floodwaters and surface runoff. One of the most effective and commonly used methods to renew soil nutrients is the management of floodwaters and runoff flows, which transport not only water but sediments and detritus abundant in organic matter. The benefits of river overflow, flash floods, and surface runoff in enhancing soil fertility are appreciated by contemporary (Nabhan 1984; Norton et al. 2001, 1998; Sandor et al. 2002) and historic Southwestern farmers (Castetter and Bell 1942; Cushing 1920).

Sediments and detritus transported by floodwaters are high in nutrients that are immediately available for crop uptake or will be later mineralized and broken down into plant-available nutrient forms. *Ak-chin* or arroyo mouth fields in particular accumulate runoff debris of partially decomposed organic litter (Nabhan 1983; 1984). Castetter and Bell (1942: 172) argue that fallowing was not necessary in the Akimel O'odham (Pima) and Tohono O'ohdam (Papago) areas of Southern Arizona because replenishment of mineral and organic materials from the annual overflow of the Gila River or from periodic flash floods allowed for continuous cultivation. Fertility renewal in the contemporary Zuni area is attributed to deposited organic material as a result of storm runoff as well as periodic fallowing (Muenchrath et al. 2002). Cushing (1920) remarked how the Zuni prepared fields and managed runoff for several seasons before growing crops, likely to allow for the mineralization of nutrients that would increase their availability for crop growth (Sandor et al. 2007). Deposition of organic debris or detritus and sediments from runoff has been observed within prehistoric agricultural modifications (Rankin 1989).

Recent research on contemporary Zuni agriculture in west-central New Mexico provides excellent documentation that runoff boosts not only water availability but also builds and replenishes soil fertility (summarized in Sandor et al. 2007). The thickened A-horizons associated with Zuni runoff field systems increase water retention after large storm events, which also add fresh mineral and organic material that replenish soil nutrients (Homburg and Sandor 2011; Homburg et al. 2005; Norton et al. 2003; Sandor et al. 2007). Runoff is a form of "traveling compost" (Sandor et al. 2007: 369). Higher quality, more decomposed organic debris is deposited with lower intensity runoff events (Sandor et al. 2007). Overall the runoff deposits in the Zuni agricultural fields are particularly nutrient-rich because of their placement downslope from forested uplands which contribute organic-rich material to runoff (Norton et al. 2007b). The benefit of "tree soil" for crop growth is something the contemporary Zuni themselves recognize and promote (Norton et al. 1998; Sandor et al. 2002).

Aeolian deposition. Deposition of dust and other wind-blown sediments also contributes nutrients to agroecosystems. Cushing (1920:165-166) describes how the Zuni would capture wind-blown dust during spring sand storms by planting sagebrush. Spring rains spread this newly deposited fertile sediment within the field. At Hopi, fertility is maintained in *ak-chin* or runoff fields by the annual accumulation of alluvium but sand dune fields require a longer cycle of replenishment from aeolian deposits (Bradfield 1971). Periodically, sand dune fields are left fallow at Hopi to allow topsoil that has blown away when the field was cleared for cultivation to be replenished. When fallow vegetation is allowed to regrow it helps capture the aeolian sediments. Fields are cleared and farmed again when there is enough topsoil replenishment to make the subsoil moist again (Bradfield 1971:18).

Just as aeolian processes can deposit sediment and renew fertility, they can erode sediment. Wind causes plant dwarfing because constant desiccation results in smaller cells and a more compact plant (Gliessman 2007). Hopi cornfields in particular are noted for their short stature; for example, Blue Corn plants are 3-4 feet tall. However, these same varieties can grow to as much as 7 feet tall in calm environments (personal experience). As discussed below, farmers use plant cover and low tillage practices to minimize erosion of sediments and damage from wind.

Intercropping. Intercropping with beans, a nitrogen fixing legume, is believed to enhance soil fertility in traditional Southwestern agroecosystems (Adams 2004; Berry 1995; Doolittle 2000). The pairing of a grain such as corn, wheat, rice, or barley with some sort of legume such as beans, peas, clovers, or vetches is found in almost every agricultural system in history (Vandermeer 1989). Intercropped systems incorporating some species of legume frequently contain more soil nitrogen than monoculture equivalents (summarized in Vandermeer 1989: Table 6.1). Wild leguminous plants can also contribute significant inputs of soil nitrogen over time, including bitterbrush (*Purshia*), buckbush (*Ceanothus*), buffalo berries (*Shepherdia*), mesquite (*Prosopis),* acacia *(Acacia)* and lupine (*Lupinus)* (Berry 1995). In the prehistoric American Southwest, prehistoric cultivated leguminous plants would have included common beans, tepary beans, Jack beans, and also possibly small lima and scarlet runner beans although they are associated with post-contact contexts (Fish 2004). However, the nutrient contribution of legumes is not as straightforward in dry environments as discussed below.

Legumes supply the nitrogen they fix to agroecosystems primarily by two processes: 1) fixed nitrogen can be sloughed off from the root nodules during the cropping cycle and taken up by a neighboring cultigen, or, 2) decomposed legume biomass (leaves, roots, unharvested grain) can remain within field soils (Sprent and Sprent 1990). In order for a nonlegume cultivar to take nitrogen attached to the roots of the legumes, both plants would have to be planted in very close spatial association. The "three sister" cropping system of planting mounds of corn, beans, and squash, common among many indigenous agriculturalists in Northeastern North America, developed as a strategy that would capitalize on these benefits (Doolittle 2000: 141; Pleasant 2006). Maize provides a stalk for the beans to climb, beans support nitrogen fixing bacteria which replace nitrogen removed during cropping, and squash plants have large leaves that cover the ground, reducing erosion from rain splash and evaporation of soil moisture by providing shade (Doolittle 2000:144). This symbiotic intercropping system is characteristic of Iroquois (Pleasant 2006) and Latin American agriculture (Gliessman 2007) but has been frequently attributed to all indigenous North American agriculture.

The bean plant itself requires most if not all of the nitrogen that it fixes for its own growth and development. This source of nitrogen can be recycled into the soil through decomposition of the plant. However, many legume plants funnel much of their nitrogen into the grain or harvestable portion rather than the portions of the plant that could be left behind in the fields to decay and release nutrients back into field soil (Amador and Gliessman 1990; Haynes et al. 1993; Sprent and Sprent 1990; Tate 2000: 348). Therefore much of the nitrogen they fix is actually removed through harvest and may not enhance nitrogen availability for other crops or be returned to the system for future use. Any factor that that leads to the loss of legume roots, leaves or grain from the system influences that ability of the plant to provide nitrogen to other plants during later cropping cycles. Within most systems, legumes fix enough nitrogen for their own requirements and thus, do not deplete soil N reserves. Incorporation of decomposing debris will influence the degree to which fixed nitrogen is recycled.

Evaluating the importance of beans in specific prehistoric agroecosystems is thus difficult. Beans are inherently less durable than maize and commonly used preparation methods like boiling are likely not to produce preserved carbonized remains. Beans are preserved sporadically in the archaeological record and instances when they are recovered are associated with dry caves and catastrophic fires (Fish 2004), rarely within field contexts. Southwestern ethnographic information from historic groups indicates beans were readily planted but the evidence does not support intensive use of intercropping or even rotational cropping of maize and beans within the same field. Among the Hopi, beans, squash and melons are planted in separate smaller plots at the edge of maize fields or in a completely separate field (Brown et al. 1952; Clark 1928;

Forde 1948; Prevost et al. 1984), and maize and beans were also planted in separate fields among the Akimel O'odham people (Castetter and Bell 1942: 155). Navajo farmers reported that beans and squash were occasionally planted with corn, but plants were smaller and less productive than if planted in separate patches (Hill 1938:34-35). Contemporary Zuni intercrop beans, watermelon, and squash although watermelon and squash were not grown together in some fields because these crops require too much water (Muenchrath et al. 2002:23). In addition, many historic accounts document the use of the same crop within a field year after year and crop rotation strategies are rare (Forde 1948:230).

It is possible that in the dry climates of the Southwest the benefits of intercropping and rotational cropping with leguminous plants are outweighed by the need to maximize available water stores. Crop production can be no greater than that allowed by the major limiting factor. In the hot, arid landscapes of Southwestern climates, this is water. The more expansive and competitive root systems of maize can mean bean crops might suffer. A study of intercropped maize and common beans (*Phaseolus vulgaris*) in semi-arid Kenya, for example, indicates that under inter-cropping, bean and maize yields were significantly reduced but post-harvest nitrogen levels were maintained or were slightly increased when compared to the pre-planting levels. In the same area, maize monocrop systems experienced a marked decline in soil nitrogen (Maingi et al. 2001). Generally, humid climates or the use of irrigation is necessary for the nitrogen benefits of legumes to be realized (Olson and Sander 1988:646).

Environments with low rainfall and extremes of temperature are also very problematic for rhizobia. Fixation is accomplished through biochemical processes mediated by rhizobial bacteria that live symbiotically on legume roots. It is not the legume plant itself that fixes nitrogen, but the colonies of rhizobia bacteria that infect legume root structures causing the growth of nodules. Decreased size and densities of rhizobia, as well as delayed growth, are associated with water stress and high soil temperatures (Bottomley et al. 1991; Tate 2000; Zahran 1999). Rhizobia associated with beans in traditional agroecosystems of the Southwest are possibility drought tolerant just as the cultigens themselves are adapted to the unique conditions of these systems. A study of the common bean (*Phaseolus vulgaris*), known as a very drought tolerant cultivar, indicated that the dry weight of this legume was not affected by water stress but the number and weight of rhizobial nodules, and therefore N_2 fixation were reduced (Ramos et al. 1999). Modern agronomic techniques that inoculate plants with competitive and drought-tolerant rhizobia are perceived as a more effective way to maximize fertility and production in water-limited systems compared to high input synthetic fertilizers (Zahran 1999).

Biological nitrogen fixation from the use of legumes can improve the N pools of soils in some agroecosystems (Sprent and Sprent 1990; Vandermeer 1989). Typically the symbiotic relationship between legumes and crops is associated with temperate agricultural systems (Tate 2000: 348). There is not always a large net increase in N, however, and this may only be a perceived benefit when a legume-cereal intercropping or rotation system is compared to just a cereal grain monocrop strategy in the same soil (Peoples et al. 1995). In sum, this review is inconclusive about the influence legumes have on nutrient renewal in prehistoric agrosystems. Microbial and agronomic studies that investigate the climate, soil, and nitrogen dynamics of the leguminous cultivars and traditional technologies used in the Southwest would be very helpful in determining the degree to which bean cultivation influenced soil fertility.

External Anthropogenic Sources. Humans can also renew nutrient fertility through the use of external sources such as garbage, ashes, manure, and urine. The Tohono O'Odham plowed under household ashes as a soil rejuvenating technique (Nabhan 1983:165) and the Zuni also took ash and hearth sweepings to fields (Stevenson 1904:108-132). The Zia packed ashes overtopped with clay soil around the bases of young maize plants (Euler 1954:28), and Adolf Bandelier reported that Rio Grande Puebloan people carried urine collected in ceramic vessels to fields (Lange and Riley 1966:104). Despite these few ethnographic references there is little evidence that external fertilizer use was a widespread practice among historic Southwestern agriculturalists. Prehistorically, there were no domesticated draft animals whose manure could be applied on fields and human waste likely would be a minimal contributor and restricted to fields and gardens located near residences.

Management of crop residue. Crop residue is a major source for organic matter decomposition in agroecosystems (Gardner et al. 1985). This requires plant residues to be left in fields. Also in order for the soil microbes to break down residue into nutrient elements they need optimal moisture and temperature optimums (Brady and Weil 2007). Crop residues are particularly rich in carbon and nitrogen and their removal is a loss of input to the soil and results in a decline of soil organic matter compared to systems where residues are retained (Franzluebbers 2004). Ethnographically, several Southwestern groups tilled under crop stubble to replace nutrients (Nabhan 1983:165). Frequently crop stubble was also left within Southwestern fields to serve as a windbreak, dust trap, or terrace to intercept runoff and would also serve as a source of decaying organic matter for subsequent years' crops (Gimenez et al. 1997; Muenchrath and Salvador 1995).

Burning. Intentional burning of crop residues or vegetation cover is one way to speed up the decomposition process. Burning to remove field vegetation has been documented for southern Arizona O'odham groups (Castetter and Bell 1942), the White Mountain Apache (Buskirk 1986), and the Zuni (Cushing 1920). Navajo traditionally burned fields to clear them of vegetation before planting, although this was more frequently done the first time a field was to be used to remove the brush and trees that would compete for water (Hill 1938:24). Many nutrients contained within burned plant cover are actually lost through volatilization to the atmosphere, particularly nitrogen, although the nitrogen that remains in the ash is more available for immediate uptake by plants compared to unburned vegetation and does not require mineralization to plant-available forms (Gliessman 2007). Due to the limited amounts of biomass in many Southwestern landscapes, it is unlikely that burning would have major nutrient replenishment benefits (see Benson 2011a for further discussion) but it would be a useful way to clear vegetation quickly.

Tillage. No-till or conservation tillage systems prevent soil disturbance, maintain soil organic matter, and reduce erosion (Pleasant 2006). Minimal tillage is associated with higher soil fertility and maintenance of soil organic matter, low bulk density, and soil-water-temperature-air dynamics that more closely resemble natural ecosystems (Olson and Sander 1988:654).

Traditional Southwestern agriculturalists used a digging stick to open the soil to place the seeds. It is not advantageous to till the entire field surface which can expose soil moisture to evaporation. The use of a digging stick reduces soil disturbance and is also an effective strategy for reducing erosion and suppressing weeds (Muenchrath and Salvador 1995).

Crop Rotation Strategies. The traditional planting in hills, or small mounds, that are then moved within a field from year to year allows for areas of the field to rest and replenish nutrients at a small scale (Adams 2004). Harvested stalks remained in the fields and provide decomposing biomass as well as indicated the location of the previous year's hill location. Cushing (1920) noted that the historic Zuni used a form of in-field fallowing in which new crops were planted about 10 to 12 cm east of the previous years' row of crop stubble. At Hopi, hills are rotated in-between the rows of stubble from preceding harvests (Beaglehole 1937:40; Forde 1931:390). Based on this information and a hill spacing of 3 m, Benson (2011a) calculated that it would be 24 years before the root mass of a maize hill would cycle back to a previously planted location. This form of in-field crop rotation may have been key to maintaining soil fertility in Southwestern agroecosystems.

Complete field fallow is and likely was also important among Southwestern traditional farmers. Contemporary Zuni farm fields for two or three years and then leave them fallow for one to four years (Muenchrath et al. 2002; Sandor et al. 2007). Nutrient deficiencies have been observed in fields used for more than several consecutive years (Muenchrath et al. 2002: 11). Contemporary Tohono O'odham also use a fallow rotation sequence (Nabhan 1983:165). Hopi only practice field fallow within sand dune fields compared to their ak-chin fields located at the base of the mesas which are annually renewed by floodwaters (Beaglehole 1937; Bradfield 1971). Entire sand dune fields are left fallow for several years to replenish topsoil that has blown away because of exposure (Bradfield 1971). Historic Western Apache "rested" a field for a year, once every two or three years (Buskirk 1986:23). Crop rotation was not practiced among the Navajo and no informants knew of a field that had become exhausted of fertility (Hill 1938:37).

Chapter 3:

THE ARCHAEOLOGICAL CASE STUDY: PERRY MESA, CENTRAL ARIZONA

The Perry Mesa landscape in central Arizona is the setting of the agroecosystem case study. Located 90 miles north of the Phoenix Basin, the canyon and mesa complex is positioned along the Agua Fria River north of Black Canyon City (Figure 3.1). The region was principally occupied by small-scale agriculturalists from ca. A.D. 900 to the early 1400s with the most intense occupation occurring from A.D. 1275-1450. This upland environment has extensive evidence of runoff agricultural land and water and soil control features, mainly terrace alignments on gentle hill slopes (Gumerman et al. 1975; Kruse 2007; Kruse 2005).

Perry Mesa is currently federally owned and managed by the Agua Fria National Monument of the Bureau of Land Management and the Tonto National Forest. In 1996, archaeologists from these agencies successfully nominated the Perry Mesa area as historic districts to the National Register of Historic Places (Stone 2000). Since that time the region has been the focus of numerous research and cultural resource management projects (Abbott and Spielmann 2013; Baker and Bruder 2002; Kruse 2005; Kruse-Peeples et al. 2009; North 2002; Spielmann et al. 2011; Watkins 2012; Wilcox and Holmlund 2007).

Environmental Context

Perry Mesa is a semiarid grassland incised by deep canyons (Figure 3.1). The region includes the landforms of Black and Perry Mesas, separated by the canyon of the Agua Fria River; tributaries of the Agua Fria, including Silver, Bishop, Perry Tank,

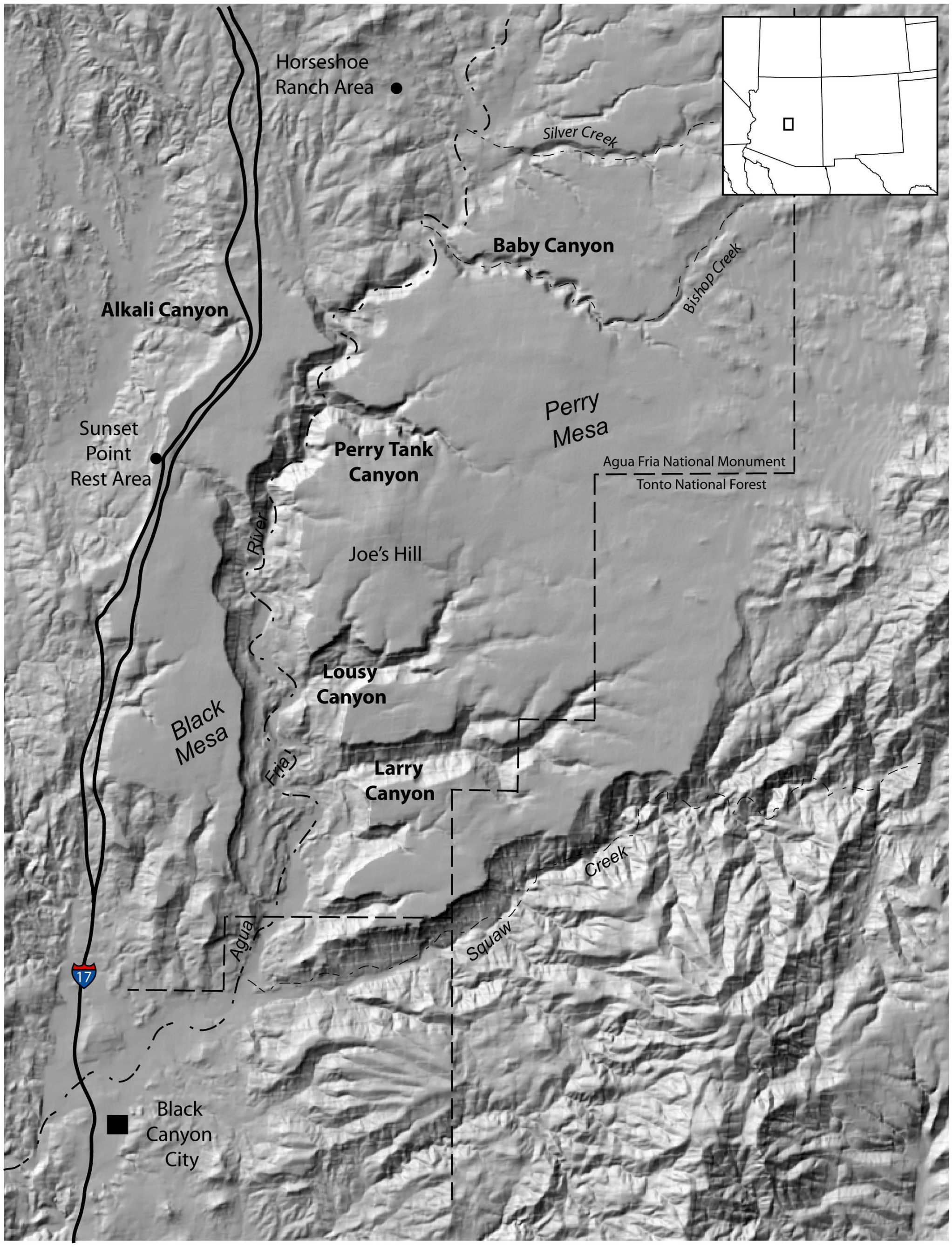


Figure 3.1. Location of the Perry Mesa region and places referred to in the text.

Larry, and Squaw Creeks, drain parts of Perry Mesa. The Bradshaw Mountains are located to the west of Black Mesa, the Black Hills lie to the northwest and the foothills of the New River Mountains are along the southeastern edge of Perry Mesa. Bloody Basin, the location of several contemporaneous Pueblo IV sites, is located to the east between Perry Mesa and the Verde Valley.

The mesa top is an area of gentle slopes and low hills. Native vegetation is tobosa and grama grasses, with catclaw acacia, prickly pear, and occasionally juniper and mesquite. The canyons are nearly vertical drops with chaparral vegetation clinging to the hillsides and riparian vegetation growing along the watercourses, including the occasional cottonwood, sycamore, and ash trees in the better-watered Agua Fria canyon. Elevation ranges from about 650 m (2100 feet) in the riparian zones to 1,400 m (4600 feet) on the mesa top.

Perry Mesa surface geologic units are Tertiary and Quaternary basaltic rocks derived from the shield volcano, Joe’s Hill, in the west-central portion of the mesa. Logically, one would assume that the soils on the mesa tops are derived from this basalt. However, recent analysis suggests that atmospheric dust deposition is also a major contributor to soil development on Perry Mesa (Nakase 2012). The basalt caps are visible along the canyon edges and come to the surface throughout the area, creating the characteristic rocky landscape visible today. Underlying the basalt are Precambrian granitic rocks and schist, which outcrop only occasionally on the mesa top but are visible in the canyons.

Climate

Perry Mesa has a semiarid climate characterized by hot and relatively dry summers and mild winters. Precipitation occurs in a bimodal pattern with a majority of rainfall occurring in the summer (mid June-Sept) and the winter (December – March). The spring and early summer (April-early June) are typically dry. Agricultural season rainfall occurs as summer monsoon storms, which are short, intense storms that build and collapse quickly and are the result of convective heating of moist air from the Gulf of Mexico. In contrast, winter precipitation is typically the result of spatially extensive frontal systems from the Pacific Ocean that are of low intensity and can persist for several hours (Sheppard et al. 2002). Snowfall or freezing rain does occasionally occur on Perry Mesa during the winter, but snow accumulation is rare.

Current annual precipitation on top of the mesa ranges from 325 mm (12.8 inches) to 357 mm (14.1 inches), with an average of 117 mm (4.6 inches) falling during the summer monsoon (Yavapai County Flood Control District, www.co.yavapai.az.us; Figures 3.2; 3.3). These averages are based only on the last 29 years of climatic records for the Sunset Point and Horseshoe Ranch weather stations, the only long-term weather stations located on the mesa landforms. Other long-term weather stations in the region with longer climatic records are located in surrounding environs and have slightly higher average and summer precipitation than stations on Perry Mesa, with the exception of Black Canyon City (Figures 3.2, 3.3). Black Canyon City is located below the mesa at a much lower elevation and, unfortunately, precipitation data are only available for the last several years, a dry period in Arizona.

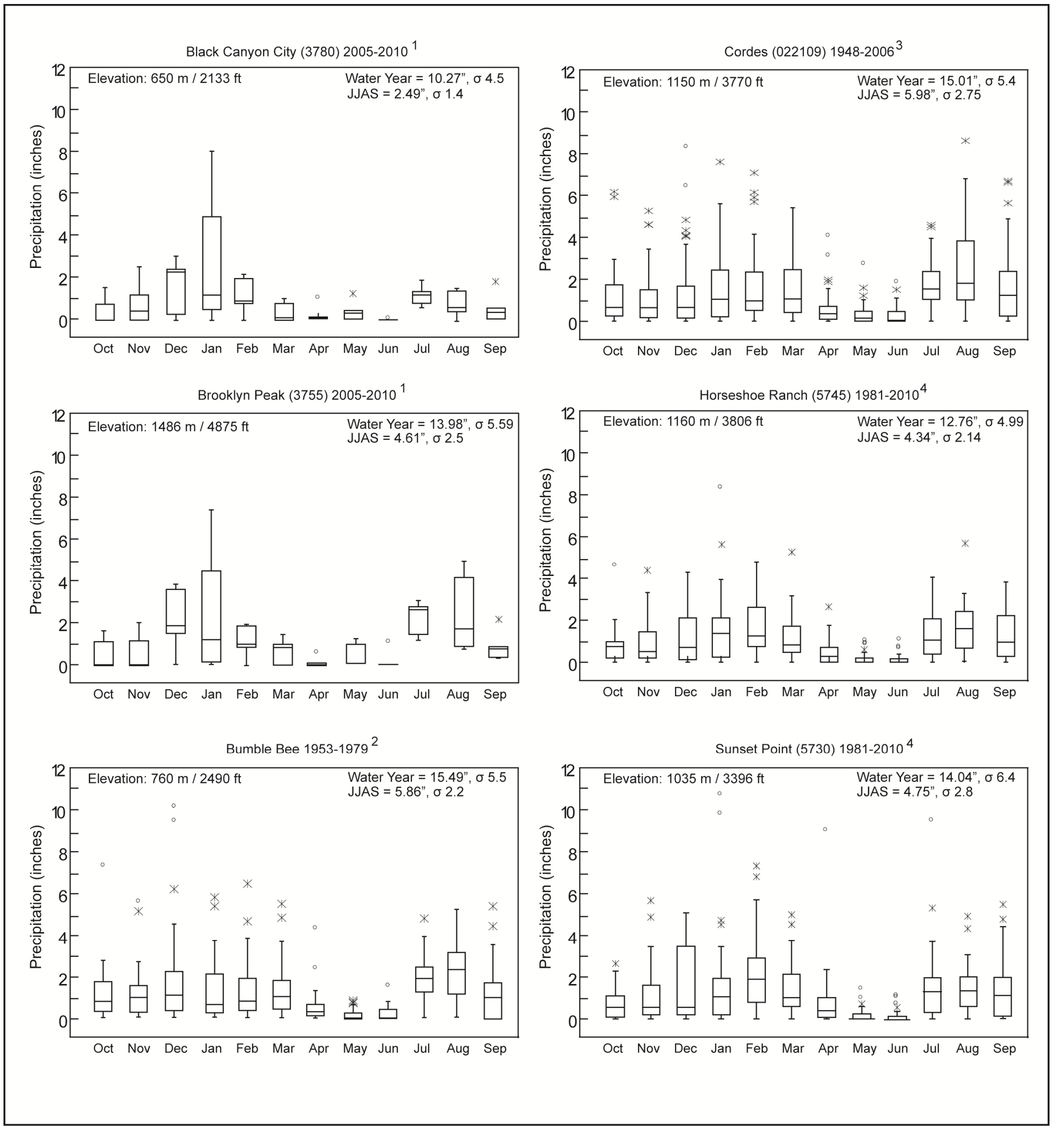


Figure 3.2. Monthly precipitation. Data from the Yavapai County Flood Control District[1] (www.co.yavapai.az.us), University of Arizona Institute of Atmospheric Physics[2] (www.atmo.arizona.edu), the Western Regional Climate Center[3] (www.wrcc.dri.edu), and the Flood Control District of Maricopa County[4] (www.fcd.maricopa.gov).

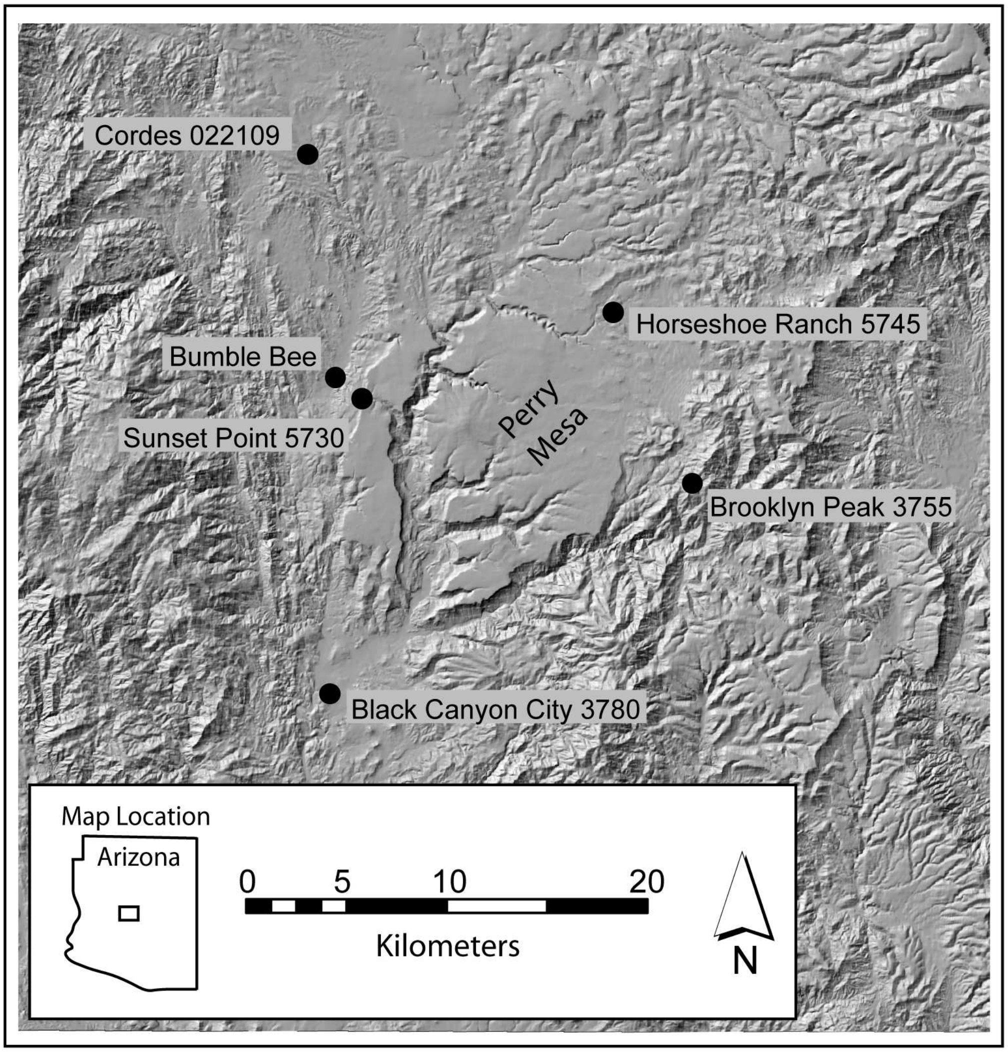


Figure 3.3. Location of regional weather stations.

Recent paleoclimatic reconstructions (Salzer and Kipfmueller 2005) based on tree-ring widths identify unprecedented wet conditions and a hiatus in dry periods during the early 14th century occupation of Perry Mesa (Ingram 2012, 2013). For example, precipitation levels during the A.D. 1321 to 1336 wet period averaged 26% above the long-term average for the 1,418 year reconstruction. The 1300 to 1338 period is also characterized by a unique 39-year hiatus in multi-year dry periods. Ingram (2012,

2013) argues that these agriculturally favorable conditions contributed to the attraction of Perry Mesa for dislocated populations on the move in the late 1200s and early 1300s and supported the population increases that occurred on the mesa.

Additional paleoenvironmental data from archaeological sites in the region also suggest wet conditions during the 14th century based on the recovery of cattail, walnut, alder, and cottonwood pollen and the possibility that perennial water supplies were available not just in the Agua Fria River but also in the smaller side drainages (Bohrer 1984; Smith 2007). Additionally, faunal remains of whistling swan and turtle indicate pools of water were available (Douglas 1997). Furthermore, petroglyph symbols related to water, such as ducks and other waterfowl, are common in the area (Stone 2000).

Perry Mesa Land Use History

To date, systematic survey has covered about 5200 ha or approximately 20% of the region and identified over 650 sites (Figure 3.4; Kruse-Peeples and Strawhacker 2012). Systematic survey has primarily occurred near the clusters of large pueblos but does include limited coverage in the center of the mesa (Ahlstrom et al. 1992; Ahlstrom and Roberts 1995; Baker and Bruder 2002; Bilsbarrow 1997; Bilsbarrow et al. 1997, 1999; Brown and Crespin 2009; Douglas 1994; Fiero et al. 1980; Fish et al. 1975; Gumerman et al. 1976; Heuett and Long 1996; Kruse-Peeples et al. 2009; North 2002; Spoerl and Gumerman 1984; Watkins 2012; Wilcox et al. 2001b: Appendix 7.1). While most archaeological remains are concentrated around the large pueblos, there are smaller residential sites, fieldhouses, agricultural field systems, petroglyphs and even racetracks features identified across the area, albeit in lower density (Ahlstrom et al. 1992; Fiero et al. 1980; Heuett and Long 1996; North 2002; Spoerl and Gumerman 1984).

The earliest evidence for human occupation of the mesa dates to the Archaic Period, represented by a few isolated projectile points and sites (Stone 2000). Small agricultural populations moved into the area during the Preclassic and Pueblo III (Early Classic) periods but this occupation was minimal compared to the population pulse of the late A.D. 1200s. The A.D. 1100-1300 in Southwestern prehistory is referred to as the PIII period or early Classic Period, and in keeping with the designation of the 14th century occupation as the Pueblo IV period, we will henceforth refer to AD 1100-1300 as the PIII occupation of Perry Mesa. The PIV period population increase occurred after A.D. 1275 and is locally identified as the Perry Mesa Tradition based on shared cultural practices.

Utilization of the greater central Arizona region by historic Yavapai bands to collect wild resources, including agave, and hunt game has been documented ethnographically (Gifford 1936). It is unlikely that historic groups farmed the uplands of Perry Mesa. Historic land use by Euro-Americans included ranching and mining activities. The grassland ecosystem present on Perry Mesa provided a rich grazing setting for cattle ranching that began in the 1870s and continues through today in a few locations. The remains of these operations are still present, as evidenced by numerous stock ponds, access roads, stone walls, and windmills. Today, the area is primarily used for recreational purposes.

Preclassic Period: A.D. 900-1150

The earliest agricultural land use in the region is from the Preclassic period prior to A.D. 1100 or 1150. There are 11 sites recorded in the area with one or more pithouses and an additional 17 sites or site components attributed to this period based on ceramics,

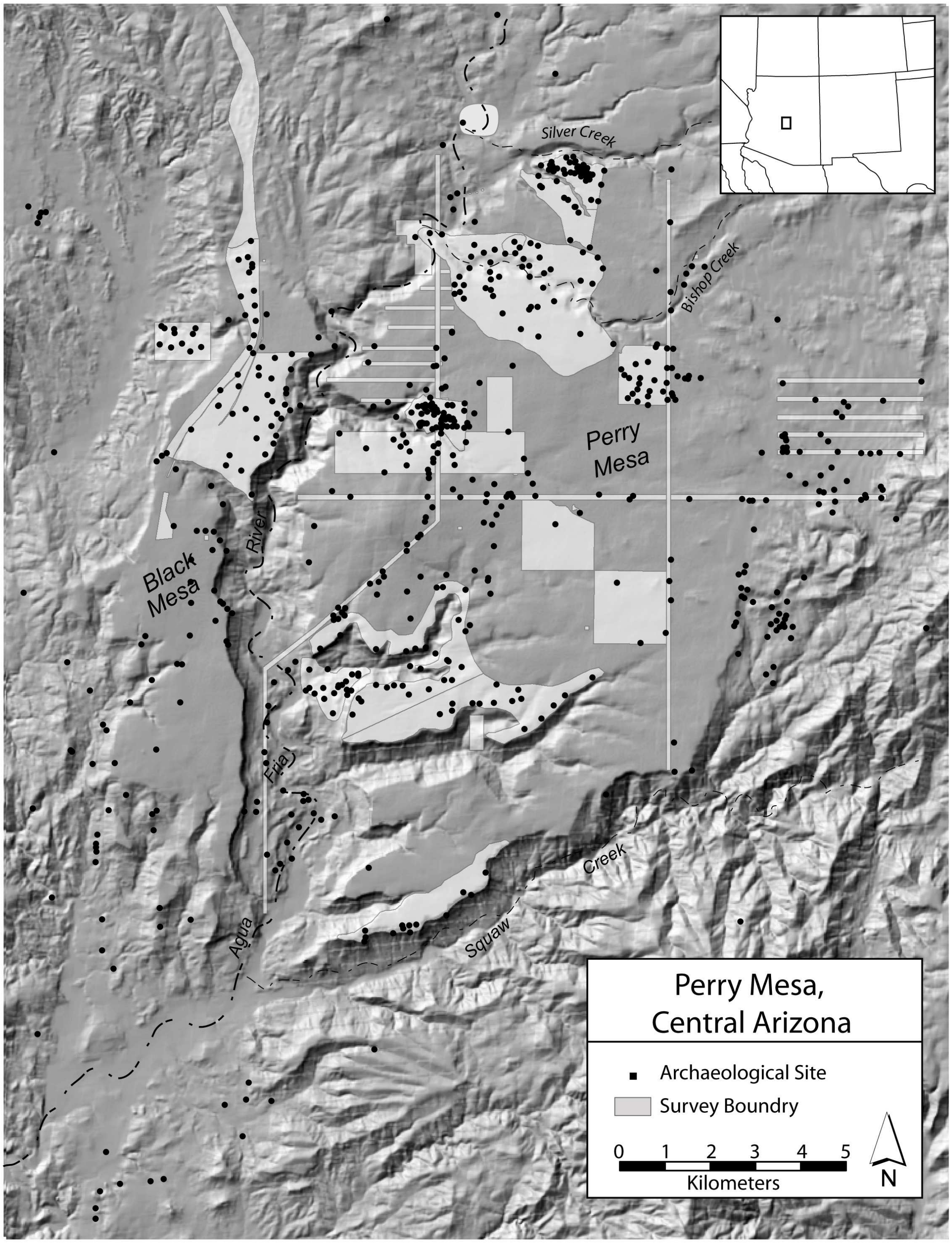


Figure 3.4. Survey coverage and site distribution in the Perry Mesa Region.

several of which are located under later PIV period sites (Kruse-Peeples and Strawhacker 2012).

Several of the pit house sites are large, covering 10 acres or more, such as NA 11304 near the center of the mesa and AR 03-12-01-1500 located on the eastern edge region near the North Campbell Cattle Tank. The locations of Preclassic pit house sites are generally in the open center of the mesa, whereas later period site locations are near the mesa edges overlooking the canyons. Scott Wood (per. comm.) has observed that many of the Preclassic pithouse sites are near old springs, now historic stock tanks, particularly along a N-S axis on the eastern side of the mesa. The Preclassic occupation of the region likely represents agricultural expansion by Hohokam populations attracted to the water present. Because sites of this period have received little attention on Perry Mesa, it is unclear if the larger pit house sites represent villages, with several contemporaneously occupied structures, or persistently occupied small farmsteads. Regardless, the pre A.D. 1150 period sites are rare compared to later periods suggesting that the Hohokam occupation of the area was neither substantial nor continuous into the major occupation pulse of the 13^{th} and 14^{th} centuries (Stone 2000:208).

Early Classic/Pueblo III Period: A.D. 1150-1275

Identification of PIII or Early Classic period sites has been problematic because some locations have been built upon by later occupations that mask the early foundations (Wood in review). Due to the difficultly in identification of earlier foundations of sites that expanded in the PIV period, it seems as though the PIII period settlement was dominated by dispersed farmsteads and hilltop settlements. Later, a shift to locations around the perimeter of the Perry Mesa region occurred at the transition to the PIV period. Recent synthesis by Wood (in review) suggests, however, that many of the large PIV settlements, particularly those towards the southern part of the mesa, had their origins during the PIII period. Regardless, the PIII period occupation was relatively small compared to the PIV period (Wood in review).

Several PIII periods sites in the region exhibit a possible defensive orientation given their location on prominent hills, the presence of certain architectural features, and patterns of intervisibility. These site types are part of a larger tradition in central Arizona of hilltop sites including forts, lookouts, retreats, and small fortified pueblos that were built between approximately A.D. 1100 and 1250 based on ceramic cross-dating (Spoerl 1984; Wilcox et al. 2001a; Wilcox et al. 2007a). The tradition of hilltop defense systems extends from the foothills north of Phoenix, along the middle and upper Agua Fria into areas north of Prescott and includes several sites on the western edge of the Perry Mesa region on Black Mesa and Alkali Canyon (Wilcox et al. 2001a:111; Wilcox and Holmlund 2007). An example of a PIII period hilltop defensive site includes NA 11646, also called the Henrie Site (Spoerl and Gumerman 1984:40). This site is located on a small isolated mesa with steep sides overlooking Black Canyon City and the Agua Fria River. It contains 13 rooms and a massive, 1.5 m thick dry-laid unfaced basalt wall with loopholes that surrounds all sites restricting access to a narrow entry point.

Other sites of this time period include small dispersed farmsteads used within a highly mobile farming strategy (Kruse-Peeples and Strawhacker 2012). It is likely that both types of sites, defensive hilltops and dispersed farmsteads, were used contemporaneously as households moved back and forth between the defendable hilltops and arable land as the social climate shifted between periods of tension and peace.

Additional research on the temporal and cultural affiliation between these types of sites needs to be undertaken.

Shifting farming locations would have been in response to seasonal resource availability, declining soil fertility and variable monsoon rainfall. Recent survey and excavation along a 270-mile pipeline corridor passing to the west of the Perry Mesa area has identified an abundance of small, short-lived single household farmsteads that precede A.D. 1275 (Brown and Crespin 2009). This type of settlement was identified by Redman (1993) for the Payson area to the east and is common in the southern Sinagua area to the north during the 1100-mid 1200s (Pilles 1996). In the latter two regions, small aggregated villages occur together with small farmsteads.

The upland, grassland environment of Perry Mesa might be a less attractive region to farm without the use of agricultural intensification and the right climatic conditions to ensure water availability to crops. The pipeline survey to the west of Perry Mesa identified approximately 4.8 Pre-Classic household communities per square mile in grassland areas (Brown and Crespin 2009).

Several dispersed, small residential farmsteads on Perry Mesa clearly date to the PIII period based on the presence of Tusayan and Little Colorado White Ware ceramics and are likely part of a similar mobile residential strategy. A few noteworthy examples include AZ N:16:264 (ASM), a small roomblock 2-4 rooms in size and associated artifact scatter with two Tusayan White Ware sherds and one Flagstaff Black-on-white, located between Larry and Perry Tank canyons (North n.d.). This site also has evidence for agricultural terracing, indicating that modification of the agricultural landscape may have occurred much earlier than the more populous PIV period. AZ N:16:278 (ASM) is a multicomponent site with 7 separate 1-4 room structures, a rock-ringed roasting pit, petroglyphs and agricultural alignments located on a bench north of the confluence of the Agua Fria River and Lousy Canyon. One feature, a 3-4 room structure associated with 10 ceramic artifacts (4 Tusayan White Ware sherds), represents a short-lived residential farmstead of the PIII period. Most of the sites identified to be a part of a PIII period residential mobility pattern lack middens but contain several rooms and therefore are interpreted to be short-term residential occupations.

Around A.D. 1275, the hilltop defense systems went out of use and areas north of Phoenix and around Prescott were depopulated (Wilcox et al. 2008:16.8). At about this time, other regions of central Arizona, including Perry Mesa and the Verde Valley, saw an immigration and aggregation of populations into larger nucleated pueblos and small villages by the 1300s (Wilcox et al. 2001b). On Perry Mesa, sites shifted location but maintained certain defensive features.

Perry Mesa Tradition: A.D. 1275-1450

During the late 1200s there was a significant increase in population on Perry Mesa and an increase in community size. This period is archaeologically known as the Perry Mesa Tradition (PMT; Stone 2000) or Perry Mesa Settlement System (Wilcox and Holmlund 2007) and corresponds to the Pueblo IV period. Sites of this period are called “large pueblos” throughout this chapter but it should be noted that villages on Perry Mesa are less than 150 rooms in size, and although large for Central Arizona, are small in comparison to PIV sites in the Southwest as a whole (Adams and Duff 2004: Table 1.1; Wilcox et al. 2007b: Table 12.2).

A recent synthesis of ceramic collections from several of the large roomblocks on Perry Mesa establishes the beginning of the PMT occupation around A.D. 1275 (Wilcox and Holmlund 2007). The end date is less certain but presumably occupation lasted until the early to mid-1400s. PMT masonry roomblocks are associated with Salado Polychromes (Cliff, Gila, Tonto, and Los Muertos types) and Jeddito and Awatovi Black-on-yellow ceramics (Wilcox and Holmlund 2007) and obsidian primarily from the Government Mountain source (Shackley 2005, 2009; Wilcox and Holmlund 2007: Appendix D).

The largest roomblocks are located in regularly spaced clusters along the canyon edges and the eastern perimeter of the Perry Mesa region (Kruse-Peeples and Strawhacker 2012). The clusters include Black Mesa, La Plata, Baby Canyon, Pato or Perry Tank, Lousy Canyon, Rosalie Mine or Hackberry Wash, Brooklyn Basin, and Las Mujeres (Figure 3.5). Each cluster typically includes 2 to 5 individual roomblocks with 45 rooms or more as well as numerous smaller 2-44 room residential structures, 1-2 room fieldhouses, agricultural field systems, petroglyph concentrations. While most archaeological sites are concentrated in these settlement clusters, there are small sites (1-2 rooms), medium-sized residential sites (2-20 rooms), and agricultural fields identified in all survey blocks (Ahlstrom et al. 1992; Fiero et al. 1980; Heuett and Long 1996; Kruse-Peeples et al. 2009; North 2002; Spoerl and Gumerman 1984). These site clusters likely functioned as dispersed villages or communities with the largest roomblocks functioning as a “center” within a cluster. Boundaries of clusters are indicated by a decrease in site density, except for the Perry Tank and Lousy Canyon clusters which have a nearly continuous distribution of sites including a few roomblocks greater than 13 rooms that cannot be assigned to a specific cluster based on location alone. Subsistence during this period focused upon maize agriculture supplemented with agave, cultivated squash and beans, and a range of wild plant and animal species (Bohrer 1984; Kruse-Peeples 2013). Agricultural strategies, discussed in depth below, were focused on runoff agriculture. GIS analysis of the agricultural landscape determined that the large settlement clusters are located on the portions of Perry Mesa that have the highest amounts of potentially arable land within a 2 km radius, indicating that population was greatest in these portions of the landscape (Kruse 2007), either due to immigration over time or aggregation. Bonding and abutting studies of wall construction within a few of the large roomblocks concluded that they were built in small segments (Schollmeyer and Nelson 2013; Hoogendyk 2011; Kiggins 2011; Mapes 2005). Without additional investigations, including excavation, it remains unclear the timespan over which segments were constructed and if individual sites have different construction sequences. Future investigations may be able to combine the implications of the agricultural landscape (Kruse 2007) and the architectural growth patterns (Schollmeyer and Nelson 2013) to determine how and why communities grew over time.

Explanations for the PIV Occupation of Perry Mesa. Wilcox and others (2001a, 2001b) interpret the settlement on Perry Mesa as part of a confederacy with contemporaneous settlements in the Verde Valley organized to guard against conflict with the Hohokam populations to the south. According to the model, the settlements on Perry Mesa were established specifically to protect the western flank of the alliance and are described as an integrated “castle” defense system. The forts and regularly spaced

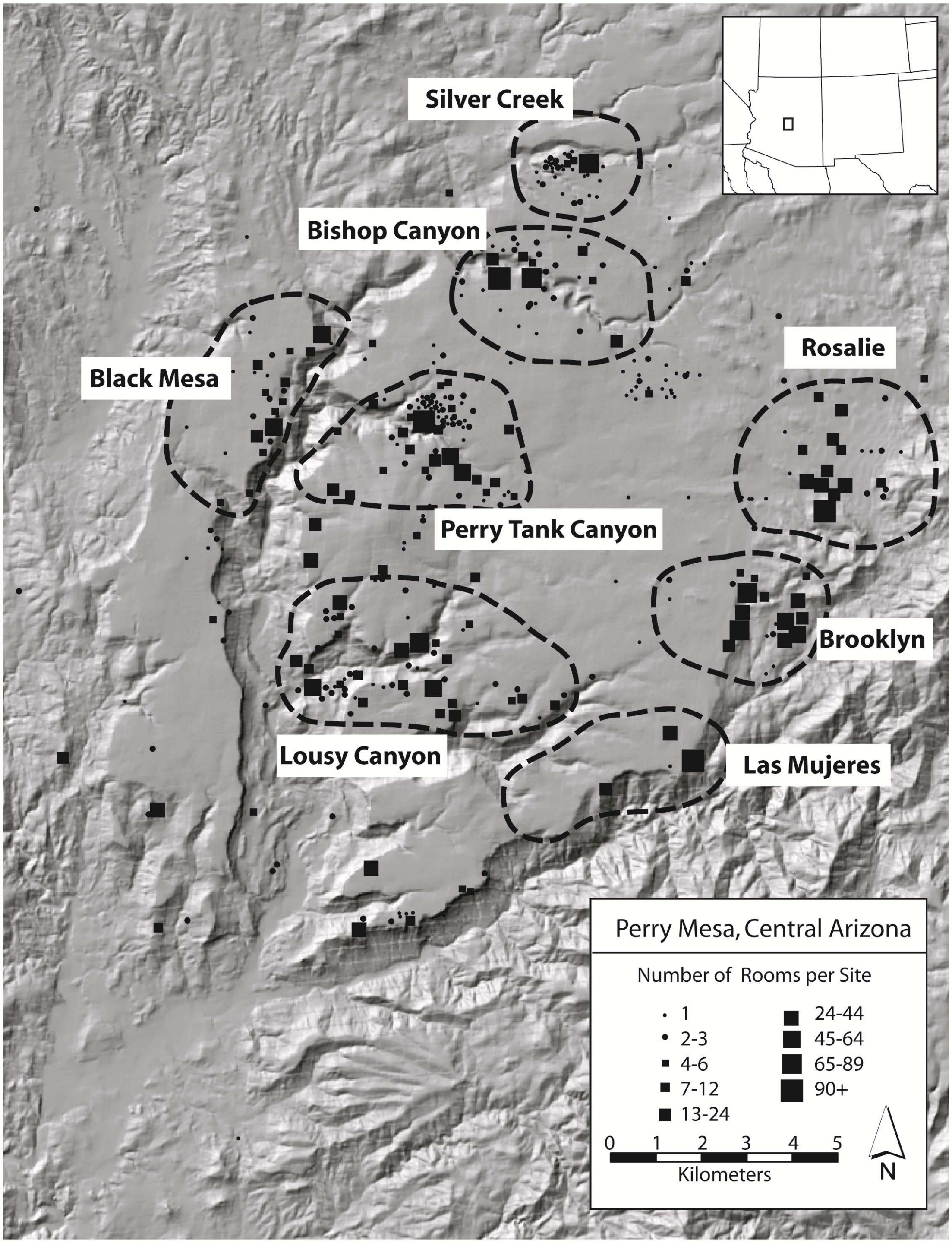


Figure 3.5. Settlement clusters of PMT component sites.

villages would serve as look-outs and signaling stations, forming an integrated communication system (Wilcox et al. 2001b). The population pulse of the 13th and 14th centuries on Perry Mesa is therefore argued to relate to interregional warfare and defense considerations.

As noted above, however, the recent GIS analysis of the Perry Mesa socio-ecological landscape has shown that large residential settlements are also located in the best places for access to agricultural land and water. Thus agricultural production may have played as much as or more of a role than defensive concerns in aggregated site placement (Kruse 2007).

The other primary explanation for the PMT pulse in occupation argues that climatic conditions during this period were favorable and may have attracted people into the area. Ingram (2009, 2011, 2013) concludes that deteriorating climatic conditions in northeastern Arizona and elsewhere, and relatively attractive conditions in portions of central Arizona are responsible for the population movement into the area during the late 1200s. In order to evaluate these two models, it is crucial to evaluate the agricultural potential of Perry Mesa (Wilcox and Holmlund 2007:note 25).

The Verde Confederacy model questions the self-sufficiency of agricultural production and postulates that Perry Mesa populations likely depended upon supplementary food from Verde Valley settlements (Wilcox and Holmlund 2007:21). The climatic explanation for movement into and out of the region suggests a direct relationship between favorable agricultural productivity and settlement (Ingram 2013). The degree to which enough food could have been reliably grown by the Perry Mesa population, however, has not been assessed. The extensive distribution of agricultural modifications (Gumerman et al.

1975; Kruse 2005; Wilcox et al 2001b:155) could indicate high agricultural potential or that farming in the region was difficult and required modification of field locations and possibly a land extensive field rotation system to produce adequate food.

A recent synthesis of subsistence related data from Perry Mesa Tradition sites argues that the combination of favorable climate, good arable land for runoff agriculture, reliance on agave, and an ideal environmental setting for wild plant and animal resources likely allowed Perry Mesa residents to have access to abundant and diversified food resources (Kruse-Peeples 2013). A more detailed evaluation of the agricultural capacity, particularly as the region was farmed for several generations, is a necessary step toward understanding Perry Mesa prehistory and is the outcome of this dissertation.

By the early to mid-1400s, human occupation of Perry Mesa decreased dramatically but the exact timing and processes that led to this depopulation are poorly understood. This was a period of population movement across the Southwest and coalescence into a few locations (Adams and Duff 2004; Hill et al. 2004). Ingram (2009) suggests that abandonment during the early 1400s coincides with an unprecedented concurrence of climatic extremes and that these deteriorating climatic conditions are key to explaining regional depopulation. Deteriorating climatic conditions would influence the ability of Perry Mesa residents to successfully produce food. What has not been explored, however, is whether decreasing productivity due to declining soil fertility may have also played a role in depopulation. Combined with the increasing climatic variability documented by Ingram (2009), farming may have been too difficult to sustain and residents left the area for more favorable conditions elsewhere. Chapter 8 evaluates this hypothesis.

The Perry Mesa Agricultural Landscape

Agricultural production in the area was dependent on dryland or rainfed agriculture. The canyon-mesa topography of the region restricts the utilization of irrigation or floodwater farming strategies that rely on surface water from the Agua Fria River or side tributaries (Kruse 2007). The canyon bottoms are extremely narrow, lack arable land, and are prone to flash flooding. There are a few locations where the floodplain is wider and certainly people utilized these locations for field placement as well. Their overall contribution, however, was likely minimal. Instead, a majority of fields were located on the gentle slopes of the mesa top to use surface runoff as a way to supplement rainfall. Runoff was directed and captured within fields by the use of stone or brush alignments, also called terraces, to direct and slow surface overland flow. This strategy is common across the American Southwest (Sandor 1995; Doolittle and Neely 2004; Wells 2003, Woodburry 1961). The Perry Mesa landscape, however, is different than some areas where runoff agriculture was practiced in that it is located in an upland environment with limited catchments versus valley margin settings which have larger catchments from which runoff is generated.

A variety of names and descriptive classification frameworks have been utilized by different authors to describe what appear to be similar features across the American Southwest (Maxwell and Anschuetz 1992, Doolittle 2000; Woosley 1980). The classification and description of Perry Mesa agricultural systems used here draws from a rich body of ethnographic (Castetter and Bell 1942; Forde 1931; Hack 1942; Nabhan 1986) and archaeological research about agricultural landscapes (Doolittle and Neely 2004; Fish et al. 1990; Wells 2003, Woodburry 1961).

Agricultural modifications identified in the Perry Mesa region can be classified into four general categories: terrace alignments, check dams, rock piles and grid systems (Kruse-Peeples 2013). Each type of agricultural modification found on Perry Mesa occurs within distinct environmental settings, and has different construction characteristics and water management capabilities. Occasionally, multiple feature types occur within a single system (Figure 3.6). The focus of this study is on the terrace systems because of their dominance and their similarity with other upland agricultural areas in the Southwest.

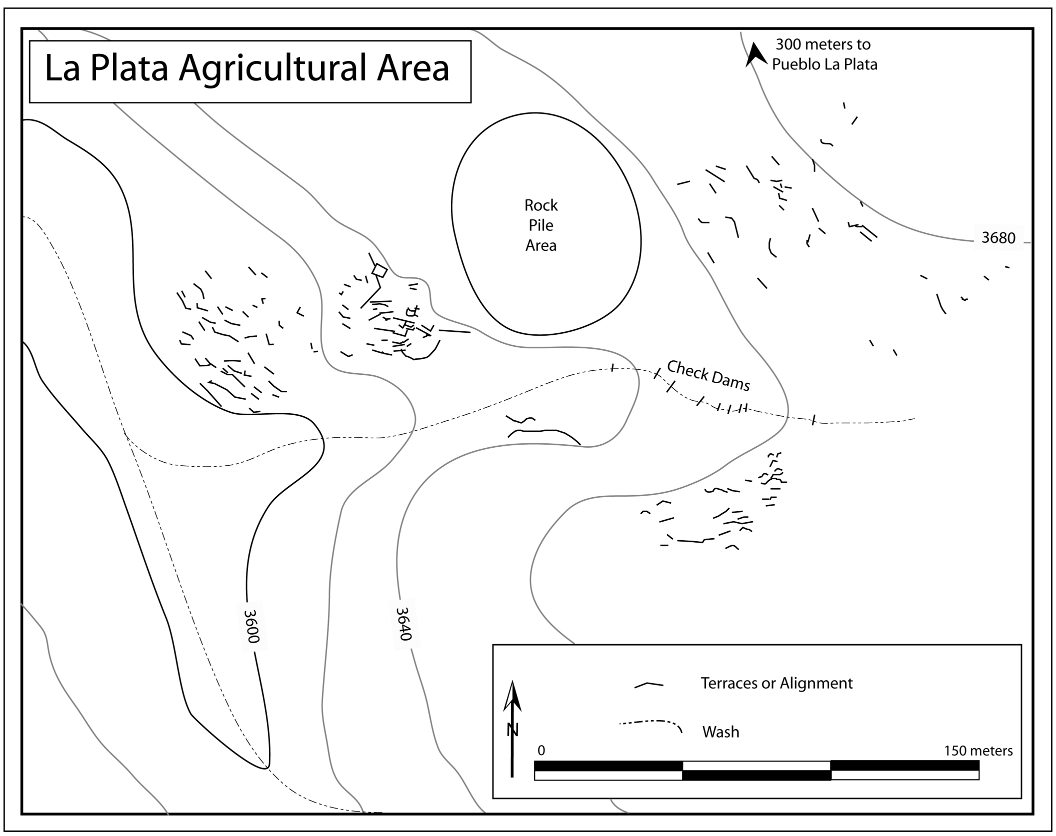


Figure 3.6. La Plata Agricultural Field showing examples of terraces, rock piles, and check dams.

Terrace features made of single courses of basalt cobbles have been identified by numerous archaeological survey areas across the entire Perry Mesa landscape (Baker and Bruder 2002; Fish et al. 1975; Gumerman et al. 1975; Heuett and Long 1996; Kruse 2005; Kruse-Peeples et al. 2009; North 2002; Wilcox and Holmlund 2007). The widespread nature of agricultural modifications indicates a great deal of agricultural investment in the landscape, despite the relatively low labor involved in constructing individual features.

Despite their extent, the environmental setting of terraced field locations is relatively constrained. Generally terraced fields are located on slopes of less than 10 percent and within small watersheds of less than 4 ha (Kruse 2007). These settings maximize the generation of runoff but minimize high velocity, potentially damaging surface flows and conform to the settings of terrace field locations in other regions of the Southwest (Sandor 1995).

A majority of terraces in the region are linear, but it is not uncommon for features to be 'U' or 'L' shaped, working with the natural topography (Figure 3.7). Agricultural terraces conform to the natural topography with some terraces using anthropogenic rock placement in combination with larger boulders to augment the natural breaks in slope. Terrace length varies between and within field systems. Some range from 3-4 m in length, but can be up to 40 m long. Typically the terraces are one to two courses high, 10 – 30 cm, and can be several courses wide, increasing in height and width as slope increases. Distance between terrace alignments varies but most are 1.5 to 3 meters apart. Most terraces occur in a series creating a system of alignments that functioned together. It is not uncommon for systems to have additional linear features constructed parallel to the slope functioning to slow and direct runoff downhill to terraces. These features are often called linear borders within the archaeological literature (Gumerman et al. 1975; Woodbury 1961).

Most terrace systems are small, consisting of a handful of terraces just a few meters in length that cover less than an acre, but there are also a few larger systems that cover more than 29 acres (Gumerman et al. 1975; Kruse-Peeples in press). Terraces provide several complementary functions such as slowing and retaining surface runoff, providing additional water, and trapping sediments and organic debris transported by the runoff, preventing erosion, and creating level planting surfaces (Doolittle 2000: 257).

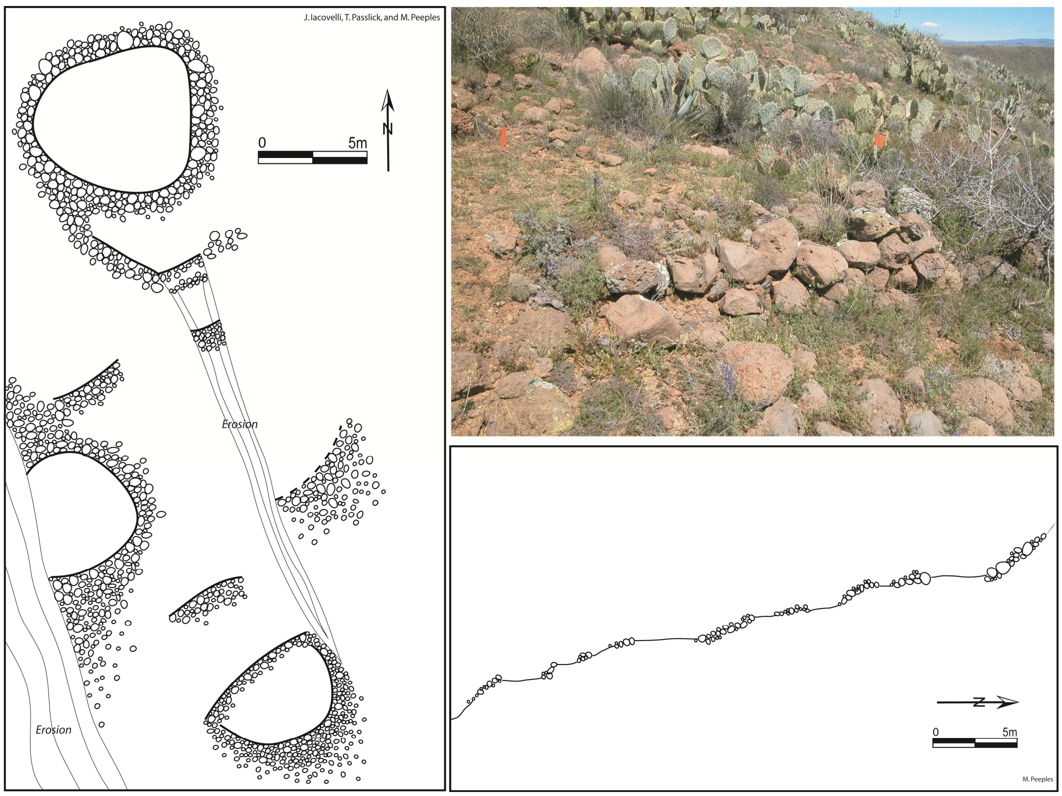


Figure 3.7. Agricultural terraces near Richinbar Ruin.

Investigations of terraced field contexts near Pueblo la Plata (Smith 2009), Richinbar Pueblo (Smith 2007), and northwest of Baby Canyon Pueblo (Fish 1980) all recovered maize pollen. Evidence for other cultigens has not been recovered from within field contexts except for a possible single cotton pollen grain from an agricultural area near Pueblo la Plata (Smith

2009). Absence of pollen from other cultigens does not preclude the use of terraced systems for crops such as beans, squash, sunflower, or little barley. For example, soil samples from modern garden plots can lack bean pollen (Gish 1993).

Unfortunately, archaeobotanical samples from midden, hearths, or architectural contexts are lacking and there is little evidence for the relative importance of different foodstuffs to Perry Mesa farmers. Samples from architectural sites, however, do provide some evidence for cultivated maize, squash, agave, and little barley (Bohrer 1984; Cummings and Puseman 1995; Kruse-Peeples 2013: Table 1). Remains from beans have not yet been recovered on Perry Mesa but their presence is likely prehistorically. Beans do not preserve well in the archaeological record and combined with the small number of excavated samples from Perry Mesa it is not surprising that clear evidence of its use has not yet been recovered.

Little barley (*Hordeum pusillum*) remains from excavated sites within the Baby Canyon area indicate deliberate human intervention in propagation as evidenced by presence of free-threshing or naked grains (Bohrer 1984). This type of grain morphology is distinctively different from native varieties and indicates anthropogenic influence on the development of the plants (Bohrer 1991). Little barley is a cool season grass that would be harvested in late spring/early summer and would have supplemented the diet at a time of year when stored maize supplies may have been depleted (Bohrer 1984:252).

Agriculture and Climate Considerations

The growing season on Perry Mesa would likely have been limited by water availability, not the threat of frost or shortened growing season. The frost-free period ranges from 179-274 days for the Cordes weather station[1] (Western Regional Climate Center 2009). The varieties of maize and other cultigens grown on Perry Mesa are unknown but this frost-free period is well within the 120 day growing season for maize. The slope orientation of Perry Mesa terraces also indicates that frost was not a consideration for farmers here. Terraced agricultural systems are often located on north and northwest facing slopes, which would limit the hours of direct sunlight to warm plants but would aid in water retention. This orientation pattern is not statistically significant, however (Kruse 2007). The onset of cooler fall temperatures may have been a problem in some years. If planting did not occur until the start of the summer monsoon period because soil moisture was not adequate to allow for spring planting, the growing season could have been too short for maize to mature

Ingram (2013) estimates precipitation levels could have been as high as 660 mm (26 inches) on Perry Mesa during the wet period from A.D. 1321 to 1336. This level of rainfall would likely be too much water for this landscape. In arid environments of the Southwest it is often assumed that more water is always better. However, the high clay content of Perry Mesa soils would easily become waterlogged and be detrimental for crop growth if a majority of this rainfall occurred during the agricultural season.

The conditions under which rainfall is delivered are important. If most of the annual rainfall occurs during the winter and spring months, this might be beneficial for agriculture if any moisture persists for spring planting and possibly be enough to sustain crops even if the summer is relatively dry. If most of the annual rainfall occurs during the summer, it is likely that crops could be washed out by high velocity runoff and that soils would become waterlogged and literally drown crop roots leading to a poor harvest. Ideal rainfall conditions are not only related to annual totals but when and how the rainfall is delivered.

Unfortunately, current tree-ring paleoclimate reconstructions do not necessarily reflect agricultural growing conditions. The data on which Ingram (in press) bases his interpretations are derived from conifer rings, which often reflect winter and early spring precipitation prior to the agricultural season. For paleoclimatic reconstructions to be accurate for modeling agricultural productivity they need to produce summer seasonal precipitation estimates.

In addition, maize experimental studies also caution against the use of cumulative growing season precipitation in predicting yields (Adams et. al 1999). In experiments by Karen Adams and others, two years with identical total growing season precipitation resulted in significantly different maize yields based on the timing and amounts of individual rain events (1999: 492). Because the growing season weather, the duration, intensity, and timing of individual rainfall events have a large influence on productivity, and paleoclimatic records are insufficient. Efforts are underway to improve the understanding of tree ring data and summer precipitation dynamics (Monson et al. 2011), but until scientists understand the relationships between paleoclimatological records and summer weather conditions, modern conditions will have to serve as a proxy for the types of rainfall events that occur under different climate regimes.

Modern climatological data indicate that summer precipitation can be quite spatially variable. Despite climatic conditions being generally more favorable and wetter during the 14th century (Ingram 2009), spatial variability likely still existed and would have influenced the agricultural land use strategy. Agricultural season rainfall in the region falls as monsoonal thunderstorms beginning in late June and lasting through September. These storms develop rapidly, are intense, short-lived, and have the potential for significant runoff (Fleming 2005). Rainfall is caused by heated air close to the ground that rises rapidly and condenses into thunderclouds, a form of convective rainfall. Where these storms pass within a season is unpredictable and highly spatially variable and rainfall is extremely localized (Goodrich et al. 1995; 2008; Hastings et al. 2005).

It is very possible that during any given year, one field system would receive adequate or abundant rainfall while a field located just a few km away would receive less rainfall, ultimately influencing yield. Long-term weather station data support this inference. Total summer precipitation in 2005 for the Sunset Point station was 2.56," whereas the Horseshoe Ranch station located across the mesa just 13 km to the east was 6.26". The following summer the pattern was reversed, with Sunset Point receiving more precipitation, an abundant 12.54", while Horseshoe Ranch received only 3.62". Moreover, the events recorded at each station were occasionally on different dates indicating the small and localized nature of storm cells.

The cumulative rainfall from monsoonal storms does become similar between locations after several years (Goodrich et al. 2008). Farmers, however, are more concerned with seasonal rainfall to ensure a good harvest from their fields. Interannual variability of rainfall has a greater effect on individual farmer behavior than decadal climate trends (Magistro and Roncoli 2000). In other arid regions of the world, erratic, spatially variable rainfall is the most limiting variable for annual agricultural productivity and influences land use strategy. Such strategies include increased number of fields planted, spatial dispersion of fields, and a higher diversity of crops planted (Graef and Haigis 2001).

Because the Perry Mesa landscape does not lend itself to reliance on flood waters, agricultural productivity is dependent on the vagaries of rainfall. The extensive distribution of terrace systems and field houses is thus argued to be a strategy of spatial diversification aimed at minimizing the risks associated with variable summer rainfall (Kruse-Peeples 2013).

Perry Mesa agricultural soils are dust-derived basalt, clay-rich soils likely beneficial to agriculture due their nutrient content. Generally, dust derived soils are high in soil nutrients and favorable for agricultural productivity (Perret and Dorel 1999). Underlying the basalt are Precambrian granitic rocks and schist which are only occasionally at the surface along the mesa edges. Sandy, granite derived soils characterize just a few terrace field locations, such as near Richinbar Ruin (Kruse-Peeples et al. 2010). The primary soil order on Perry Mesa, including those that were used for agriculture, are Vertisols, characterized as fine, montmorillonitic, mesic Aridic Haplusterts (NRCS 2011). Vertisols are dominated by shrink-swell clays that form deep, wide cracks during drying and wetting cycles (Mermut et al. 1996). While adequate for crop production in relatively mesic climates, these soils are generally classified as poor agricultural soils when located in semi-arid and arid climates due to their tendency to crack when dry, exposing plant roots, and to swell during the wet growing season, possibly restricting oxygen availability (Coulombe et al. 1996). Recent soil investigations have documented that terracing appears to have enhanced the silt and sand fraction of soils on Perry Mesa and thus altered soil textures to a more agriculturally favorable loam textures (Kruse-Peeples 2010). Decreases of clay in terraced context may have minimized Vertisol cracking. Investigations presented in Chapter 4 address the soil characteristics of Perry Mesa agricultural fields in more detail.

Chapter 3 Notes

[1] The Cordes station frost-free period is mentioned here because it has the longest record of the surrounding weather stations (58 years) and is at a similar elevation to Perry Mesa. Data from stations on Perry Mesa indicate similar frost-free periods, though the record is only ca. 20 years.

Chapter 4:

CHARACTERISTICS OF THE PERRY MESA RUNOFF AGROECOSYSTEM

In order to assess agroecosystem conditions on Perry Mesa, several field studies were undertaken, including the excavation of trenches (current chapter), soil moisture retention studies (Chapter 5), and runoff collection studies (Chapter 6). This chapter introduces the location where field studies were undertaken, the Bull Tank Agricultural Field, by describing the agricultural terraces and soil characteristics. This introduction will set up the context for the additional field analyses discussed later in the dissertation. The goal of the chapter is to characterize a runoff agroecosystem in an upland terrace agricultural setting as well as to present values that will be used for parameters of a simulation model of long-term maize growth presented in Chapter 7.

All of the field analysis employed a paired sampling design, with samples originating from modified terrace locations and unmodified locations that have similar environmental settings and ecological conditions. The paired sample strategy allowed for comparison of data from presumed cultivated contexts, terraces, and presumed uncultivated contexts, non-terraced locations.

Summary of Previous Studies on Perry Mesa

The design of the field study, sample analyses, and interpretation of the results benefited from in-depth investigations of soils from other runoff agricultural terraces on Perry Mesa (Fish 1980; Kruse 2007; Kruse-Peeples et al. 2010; Nakase 2012; Smith 2007, 2009; Spielmann et al. 2011; Trujillo 2011). These studies of Perry Mesa agricultural fields have concluded that there are relatively few chemical alterations of prehistorically farmed soils. For example, results from soil analysis from prehistoric terraced agricultural systems near Pueblo la Plata indicate there is little difference in terms of soil nutrient concentration between prehistoric anthropogenic terraces, natural geologic terraces, and adjacent non-terraced areas (Trujillo 2011). One of the only significant differences is that soils behind both natural rock alignments and anthropogenic terraces exhibit lower rates of potential nitrogen mineralization during summer and fall seasons when compared to soils in open areas not upslope from a rock barrier (Tujillo 2011). Potential nitrogen mineralization measures the release of inorganic nitrogen from organic matter by soil microorganisms and is a proxy for nitrogen availability for plants.

Recently, Nakase (2012) has argued that eolian deposition has homogenized the surface soil, reducing the spatial heterogeneity of soils. Any differences in soil nutrient content of surface soils due to prehistoric agricultural activities that may have existed have since been homogenized by 700 years of dust deposition. Chemical analyses suggest that soils on Perry Mesa are largely derived from dust accumulation as opposed to bedrock weathering, and the rate of deposition may have been important in replenishing mineral derived nutrients, P and K, extracted by agricultural crops (Nakase 2012). Due to the longer rates of phosphorus and potassium cycling and the semi-arid context of this landscape, it is likely that nitrogen would have been the most limited mineral for crop production.

The largest differences between soils from anthropogenically modified areas and soils from control areas are differences in the physical properties of soil, specifically texture. Soils from terraced contexts within studies near Richinbar Ruin and Pueblo la Plata are more frequently a coarser texture whereas non-terraced areas have higher clay fractions (Kruse-Peeples et al. 2010; Spielmann et al. 2011). Additional findings in another set of terraces near Pueblo la Plata show that soils behind anthropogenic alignments were generally coarser in texture, containing more silt and sand and less clay (Nakase 2012). Interestingly, however, soil behind natural alignments was more clayey than soils not bounded by alignments (Nakase 2012). I believe, based on runoff collection studies discussed in Chapter 6, this pattern may result from the greater frequency of runoff events within anthropogenic terraces areas and the lack of terrace maintenance. Fine particles are more easily picked up during runoff events and floated away from anthropogenic terrace surfaces (Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Parsons et al. 1991; Appendix C).

An additional difference in the physical properties of soils between inferred cultivated and uncultivated contexts is the bulk density of soils, an indicator of compaction. Bulk density was higher within a set of well-constructed terraces south of Pueblo la Plata compared to non-terraces soils, resulting in a slower rate of water infiltration within terraces (Johnson 2005).

Study Location: The Bull Tank Agricultural Area

The Bull Tank Agricultural Field (AZ N:16:352 (ASM), Figures 4.1, 4.2, 4.3) served as the location of the soil, runoff, and water content analyses presented in this dissertation. The site is located 400 m north of the rim of Baby Canyon and 300 m southeast of cattle tank for which the field is named. This field was selected as the study site because there are many terraces (over 200) to use for soil and runoff sample replication, because the field is situated in an environmental setting similar to the majority of agricultural systems on Perry Mesa (Kruse 2007), and it was logistically feasible for the number of site revisits required for this study (Figures 4.1, 4.2).

The agricultural features are located just below a hill summit and span 200 m along a 2-3 degree northwest facing slope. Terrace features are typically 10-15 meters long, 2-3 courses wide, 2 courses high, and are predominantly constructed out of unmodified cobbles (7.6-25 cm) and stone (25-60 cm) sized rocks, occasionally incorporating small boulders (>60cm) into their construction. At this site, terraces cover the slope like a large staircase from the bottom to the top of the hill. Behind each terrace is a relatively flat surface with few surface stones compared to areas where no terraces were built. The flat surfaces likely served as the actual planting areas and were between 1 and 3 meters wide and continue for the length of the terrace.

The major difference between the Bull Tank Agricultural Area and other terraced field systems on Perry Mesa is its size of 10 ha. While there are other large systems like Bull Tank, including the expansive terraced fields near Pueblo Pato, a majority of prehistoric field systems include less than 10 terrace features and cover an area less than 0.5 ha (Kruse 2007). It is not known whether this field system is larger because it was used for a longer period of time or more intensively than smaller systems in the area. The individual features, however, are representative of terrace features located on Perry Mesa, even if the size of the overall system is larger.

As indicated by the map of Bull Tank (Figure 4.2), the entire area is not covered by terraces and associated planting surfaces. Interspersed between the terraces are unmodified areas, referred to as non-terraced areas. Non-terrace locations were identified by the lack of anthropogenic terrace construction or rock clearance and are characterized by continuous surface rock and large boulder outcrops. It is likely that these areas were uncultivated prehistorically, but this is difficult to determine. Pollen samples from a terrace field system a kilometer north of Bull Tank near Pueblo la Plata revealed maize pollen from unmodified, non-terrace contexts more frequently than within the terrace contexts (Smith 2009). This pattern is counter to expectations but may be the result of maize pollen being dispersed upwind of planting locations, stacking corn outside of planting areas, or planting maize in the unmodified locations. It is likely that terraces lacked cultigen pollen because of greater disturbance of the prehistoric agricultural surface and subsequent deflation. We can never be certain of which contexts were farmed and which were not based on archaeological evidence. We can, however, be certain of which contexts were anthropogenically modified based on the presence of terraces.

There are 5 separate 1 or 1-2 room structures located in the Bull Tank field system (Kruse-Peeples and Lulewicz 2012; Figure 4.2: BT 1-5). These structures are inferred to be temporarily utilized fieldhouses as opposed to more permanent small residential pueblos based on the low density of artifacts, lack of wall rubble, presence of only 1 or 2 rooms per architectural mound, and their close proximity to agricultural features. Non-diagnostic sherds, flakes, and tabular tools occur at a low density throughout the field system. The closest residential site to the Bull Tank agricultural field is N:16:28 (ASM), a 6-8 room pueblo with a defensive wall and gridded gardens, located 400 m to the southeast (Kruse-Peeples et al. 2009). Baby Canyon Pueblo (N:16:45 (ASM)), one of the large 100+ room aggregated pueblos on Perry Mesa, is located 900 m southwest of Bull Tank, across the deeply incised canyon of the same name.

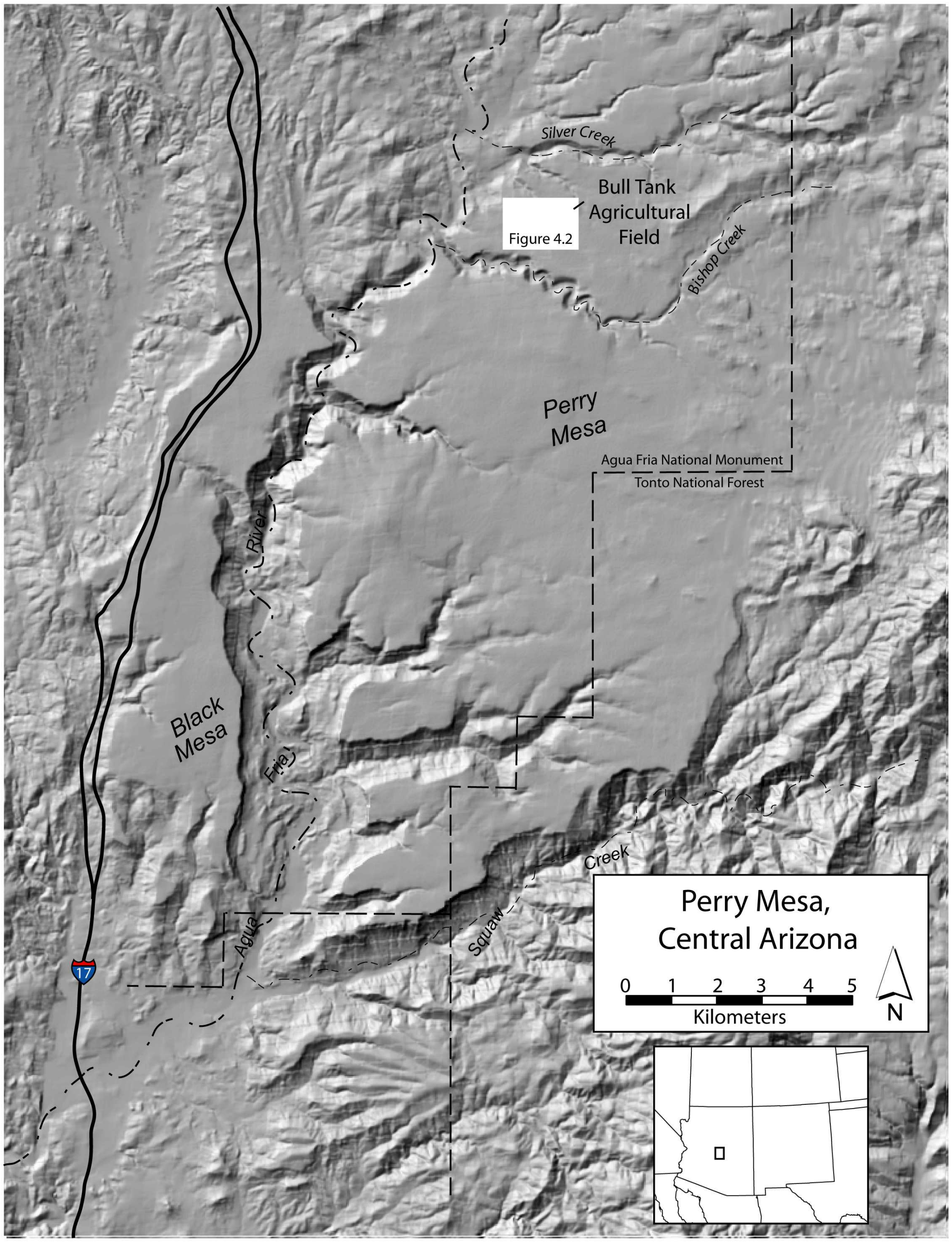


Figure 4.1. Location of the Bull Tank Agricultural Field in the Perry Mesa region.

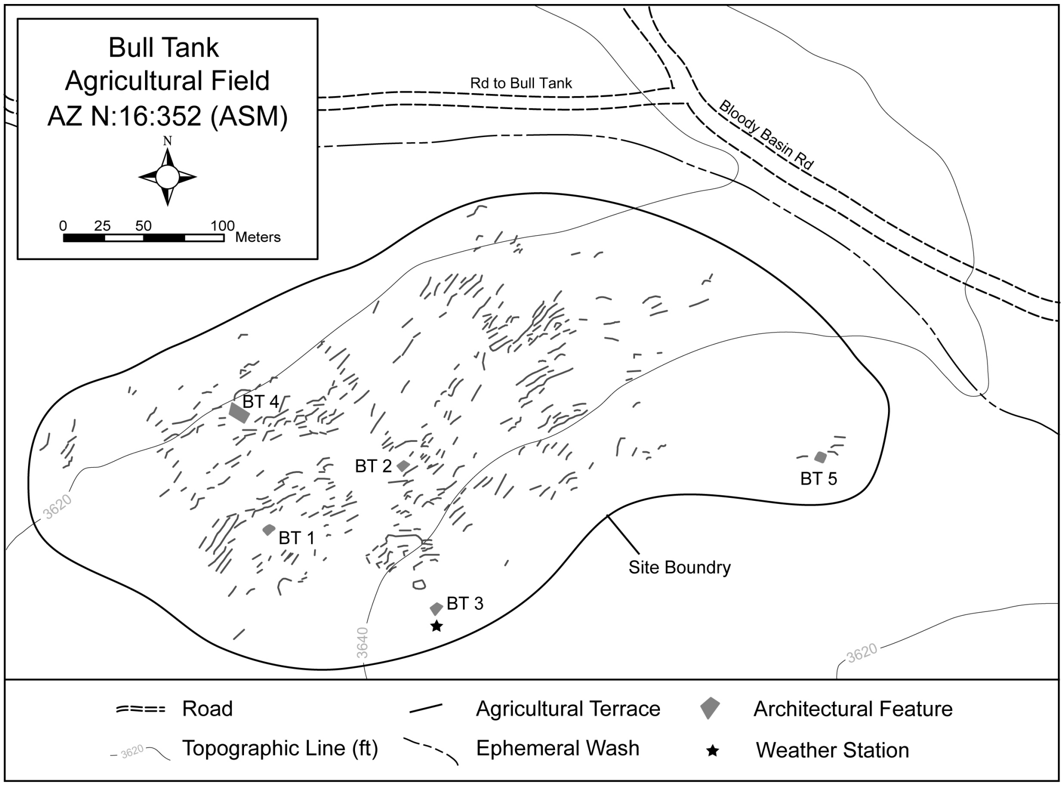


Figure 4.2. Map of the Bull Tank Agricultural Field.

Figure 4.3. Photo of the Bull Tank Agricultural Field looking southeast.

Physical and Chemical Characteristics of Terrace and Non-terrace Soils: Trench Excavations

A series of trenches was excavated in order to understand the soil properties in the Bull Tank Agricultural Field. Information about soil physical properties (bulk density, structure, texture) and chemical properties (nutrient content) was collected from these trenches. Excavation of trenches across agricultural terraces also provided information on how terraces were constructed and the effects that the walls may have had on soil deposition.

Methods and Procedures

Eight trenches, four across terraces and four within adjacent non-terraced locations, were hand-excavated across an upslope to downslope transect in the eastern half of the Bull Tank field system (Figure 4.4). The terrace trenches were located so that the excavated area would bisect an entire planting surface between two stone alignments to expose a terrace and planting surface in profile and the construction of the upslope terrace. Non-terrace area trenches were located in an unmodified location at least 15 meters from terrace trenches and were at least 1 meter in length. Width of excavated trenches did not exceed 50 cm, impeded by bedrock. This paired-site sampling strategy was used to compare soil characteristics between an inferred prehistorically cultivated area, the terraces, and unmodified locations inferred to have no or little prehistoric cultivation, the non-terraces, along a similar slope gradient. Paired site comparisons are frequently used to evaluate anthropogenic changes to soil from ancient agricultural activities (e.g., Homburg et al. 2004; Nakase 2012; Sandor and Eash 1991; Sandor et al.

1986, 1990; Sullivan 2000). The paired sample strategy was also used in the additional field studies discussed in Chapters 5 and 6.

Soils profile characteristics (e.g., depth, color, texture, structure, and consistency) were described according to procedures outlined by the Natural Resources Conservation Service – U.S. Department of Agricultural (Schoeneberger et al. 2002). All trenches were excavated to C horizon depth which is composed of highly degraded and unconsolidated basalt stones and cobbles. A soil sample was collected from each stratum from the west face of each exposed terrace planting surface, two per trench, and the non-terrace trench profiles, one per trench. Trenches were located at least one m away from any nitrogen-fixing microbial cat claw acacia shrubs (*Acacia greggii*).

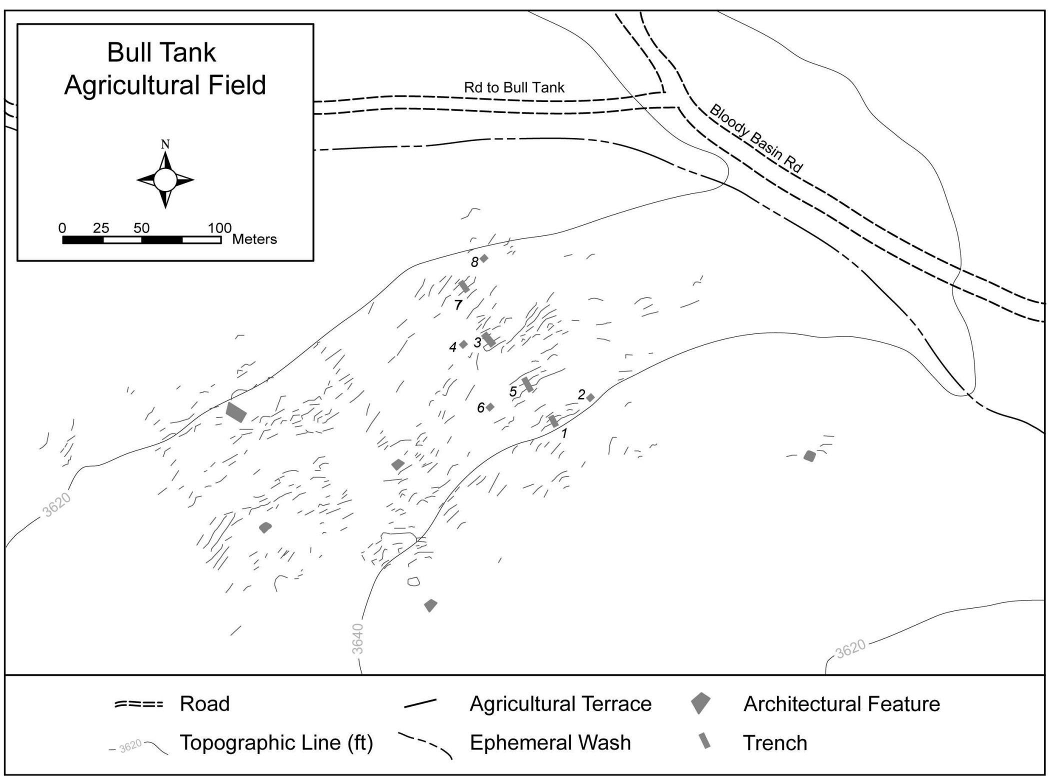


Figure 4.4. Location of trenches (1-8) within the Bull Tank Agricultural Field.

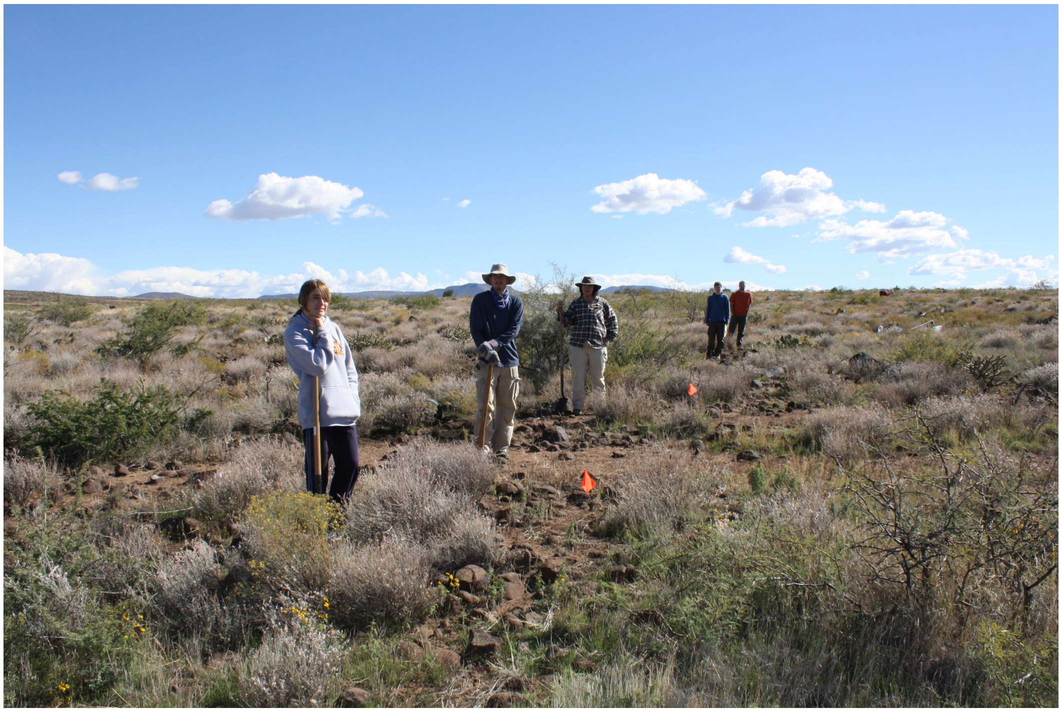


Figure 4.5. Photograph of Trench 7 (marked by orange flags). Each person is standing on a separate terrace planting surface.

Analyses

After field collection, soil samples were transported on ice to the Terrestrial Ecosystem Ecology Laboratory at Arizona State University for overnight storage. Samples were sieved to 2 mm to remove the gravel fraction and homogenize the sample before bulk analysis preparation the following day. Analysis of bulk samples included texture (particle size), soil organic matter, total carbon, total and inorganic nitrogen, available phosphate, and water holding capacity (WHC) (Table 4.1). Soils from Perry Mesa have very low to no carbonates (Hall et al. in prep) and therefore total carbon content is assumed to be very similar to or the same as organic carbon levels. Data, however, are presented as total carbon.

Table 4.1. Summary of bulk soil analyses and methods.

Analysis	Method
Bulk Density (g/cm^{-3})	A horizon samples determined by the core method. Gravel fraction (>2mm) weight and volume were subtracted. Bt horizons determined by clod method (Dane & Topp 2002). Volume of an intact paraffin coated ped was estimated by water displacement, gravel (>2mm) weight and volume within the ped was removed and subtracted resulting in final calculation (g/cm^{-3}).
Particle Size (<2mm, %)	Hydrometer method (Gee and Or 2002). Samples pretreated with sodium hexametaphosphate solution for clay dispersion. Hydrometer readings followed by sieving to 53 µm for sand fraction and determination of silt fraction by difference. Particle-size distribution is classified as gravels (> 2 mm), sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (less than 0.002 mm).
Organic Matter (%)	Loss-on-ignition (LOI). Ash-free dry mass recorded after combustion of 30 g oven-dried soils for 6 hours at 550°C (Sparks 1996).
Total Carbon and Nitrogen (g/kg^{-1})	Dry combustion/gas chromatography using a Costech ECS 4010 CHNSO Analyzer (Costech Analytical Technologies, Inc., Valencia, California, USA) at ASU, Tempe, AZ. Subsamples were pre-ground using a steel ball mill to pass a 76 µm sieve (Sparks 1996).
Available P (mg/kg^{-1})	Olsen extraction method (extract of 0.5 M $NaHCO_3$, Olsen and Sommers 1982). Filtrate colorimetrically analyzed using a Bran-Luebbe Traacs 800 Autoanalyzer (SEAL Analytical Inc. Mequon WI) at ASU, Tempe, AZ.
Water Holding Capacity (%)	Gravitational water (%) held in 20 g soil after 24 hours of draining through a GF-A filter. Presented as WHC.

Results

Results of the trench excavations are presented in three sections. First, information about how terraces were constructed is discussed followed by a description of soil profiles. Terraces appear to be constructed by removing surface stones and concentrating them in linear alignments on top of and in-between concentrations of large, immovable rocks. Soil profiles exhibit variability related to hillslope location but soil strata in terraces are generally thicker than the non-terrace locations. The final results section discusses the physical and chemical properties of soils based on bulk soil samples collected from each trench. Major differences between terrace and non-terrace soils are related to physical differences such as a lower clay content of terrace soils resulting in lower water-holding capacity. Nutrient analyses indicate only slightly elevated organic matter and total carbon in non-terraced subsurface horizons. No other statistically significant nutrient differences were found between terraces and non-terraces. Explanations for the processes that resulted in the observed differences are provided. The results are followed by a discussion of what the differences between terraces and non-terraces mean for reconstructing agricultural productivity on Perry Mesa.

Terrace construction. No artifacts were recovered in the trench excavations, and therefore the inferred date of the field system is that of nearby residential pueblos, A.D. 1275 to 1450 (Stone 2000; Wilcox and Holmlund 2007). Recent surface archaeological investigations at the small roombocks south of the Bull Tank features identified phyllite tempered pottery associated with pre A.D. 1275 occupations (Abbott, personal communication). It possible that the terrace system was used throughout the 13th century.

The features are made from unmodified locally available basalt. The A horizons in many locations appear truncated by terrace stones as opposed to running underneath the stones of the terrace indicating that the features were likely constructed by using stones that were already in place. Much of the surface soils behind the terrace stones were likely deposited by relatively local sedimentation via alluvial and colluvial processes. No distinct depositional episodes were visible in any profile. Depositional events are more commonly seen in terraces constructed across ephemeral washes (e.g., Smith and Price 1994). There is no evidence from the Bull Tank trench excavations that soil was deliberately brought to in-fill the terraces as has been observed within a field system near Richinbar Ruin (Spielmann et al. 2011). The Bt horizons (designated as Bt1 and Bt2) continue on both sides of most terraces, except for Terrace 1, Trench 3 and Terrace 2, Trench 7, indicating these horizons were present before terrace construction.

The terrace profiles (Figure 4.6) show how these features were built. A majority of rocks used in terrace construction appear to be limited to the surface, and extend to depths of 5-20 cm below ground. The position of the stones in the Terrace 1 walls in both Trenches 1 and 3 indicates that these features were never free-standing walls. Rather it appears that surface construction occurred where large and small subsurface rocks were already concentrated. Numerous open spaces are present within the rock concentrations of the Bt horizons indicating that they were likely not of anthropogenic or planned origin. Given the natural rockiness of the Perry Mesa volcanic landscape, it would have been easier to create alignments by clearing away stones from the surface and placing them in areas where subsurface rocks were already concentrated than it would have been to remove subsurface stones. Many terraces in the Bull Tank field system incorporate large, immovable boulders into their construction.

Terrace construction such as this likely occurred incrementally over time as the area was cultivated (Doolittle 1984). This type of progressive modification of agricultural systems has been called the “process-rather-than- the-project approach” to agricultural modification because little labor is invested during any one event (Wilken 1987:100).

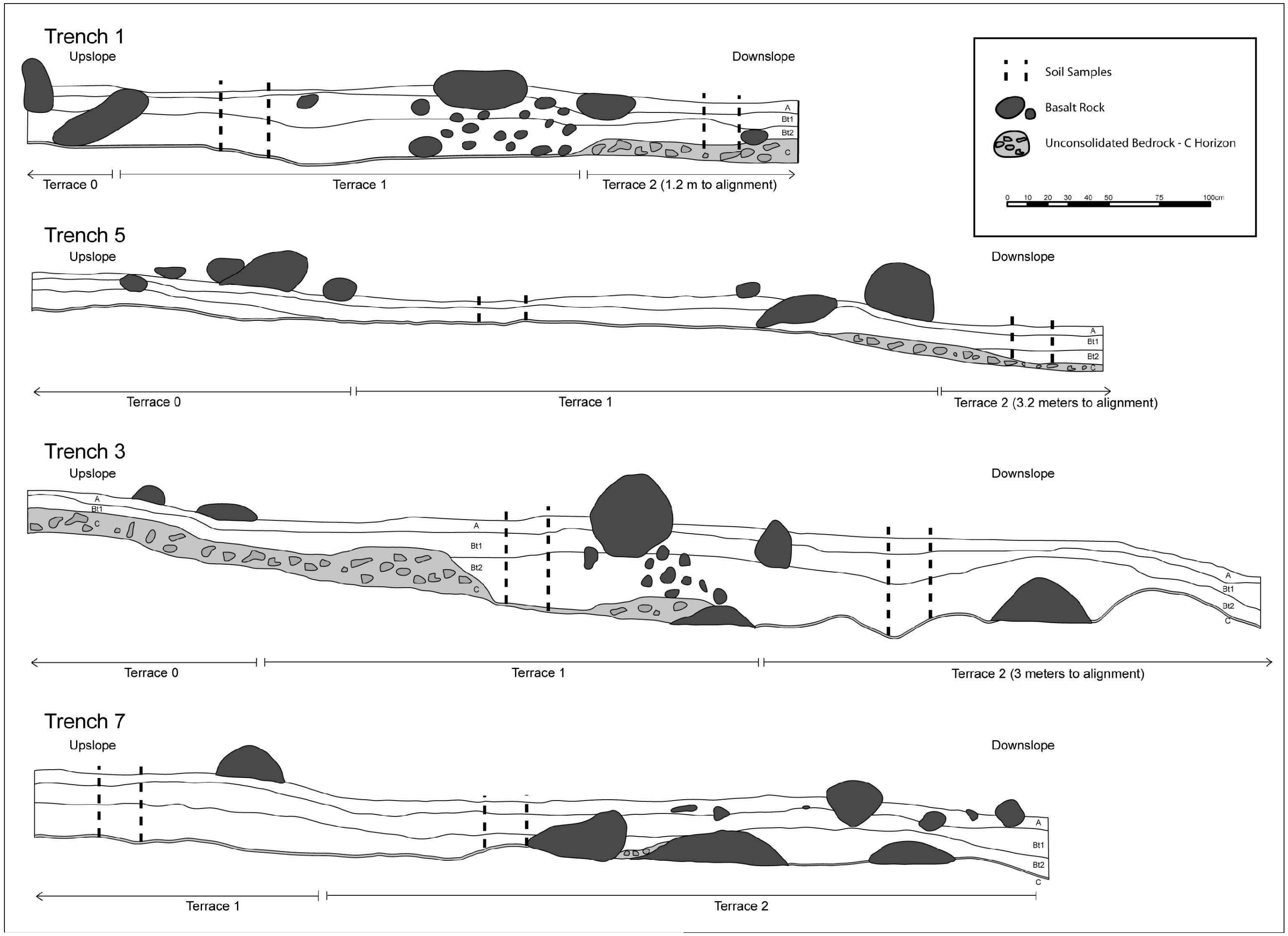


Figure 4.6. Profile maps of trenches 1, 3, 5, and 7.

Experimental evidence indicates that sedimentation of small terraces similar to Bull Tank can occur over a short time, usually within a year depending upon the intensity and frequency of runoff events transporting sediment (Sandor 1983:62-66). When terraces are not maintained, runoff would likely begin to flow between stones, eventually washing some away, preventing sedimentation. Deteriorating terracing would also influence velocity, possibly allowing erosion of more sediment than would be deposited.

Profile Descriptions. All profiles have a thin A horizon, 3-5 cm thick, underlain by a thicker Bt horizon (Figures 4.7, 4.8, Appendix 1). In most cases Bt horizons were divided into different strata (Bt1, Bt2, etc.) based on slight differences in structure and color as well as observed increases in bulk density and clay fractions. Often there were clear, abrupt boundaries between Bt strata. Clays have accumulated in higher proportions in the subsoil, compared to the topsoil, which contributes to the designation of a Bt or argillic horizon of these profiles (Schoeneberger et al. 2002). Subsoil clay accumulation provides moisture retention which is important in dryland agriculture (Homburg 2000; Homburg et al. 2004; Homburg and Sandor 1997; Sandor et al. 1990). It is better, however, for rooting zones to be underlain by, rather than composed of, subsurface argillic horizons (see Sandor 2005: 121 for summary) because this type of horizon tends to limit downward infiltration and distribution of soil water (McAuliffe 1994). The high amounts of clay within the root zone may have been *too* high but the accumulations of clays are lower in the terrace profiles compared to the non-terrace soils, possibly indicating terrace soils were more suitable for cultivation.

Subsoil structure is very blocky and massive and has the tendency to form large peds that are extremely difficult to break apart, particularly in non-terrace subsoils.

Horizon boundaries are abrupt suggesting little bioturbation. However, deep cracks were visible in some profiles and reflect the vertic properties of soils in this area. Although no systematic measuring of cracks was undertaken, cracks in non-terraces compared to terrace profiles appear to be deeper, wider, and more abundant (Figure 4.8). Cracking of this nature would be detrimental to crop production if they occurred during the agricultural season as the deep fissures would rip open and damage plant roots. Most of the observed cracks occurs during the dry months of May and November, not within the growing season. Cracking would also be a mechanism to distribute nutrients throughout the soil profile which would benefit crop growth by brining surface organic matter deeper into the root zone.

Soil horizons exhibit variation across the slope and therefore differences in bulk soil analysis, particularly thickness and particle size. These differences may be better explained by where the trench is located along the slope than the terrace or non-terrace context because variations in soil profiles are largely the result of changes in slope gradient (Birkeland 1999; Burke et al. 1995; Schimel et al. 1985). The most notable differences between paired sample locations are that upslope terrace contexts have deeper soil profiles compared to their respective non-terrace locations (Figure 4.7), although terrace soil profile depths are highly variable. Individual stratum thickness, however, increases with depth (Table 4.2; Figure 4.9).

Physical and Chemical Characteristics of Soils. A total of 37 bulk soil samples was collected and analyzed from the trenches (23 from terraces and 14 from non-terraces) (Appendix 1, 2). Paired t-tests were used to test for overall differences between the paired terrace and non-terrace trenches (Table 4.2, 4.3). Visual displays of sample

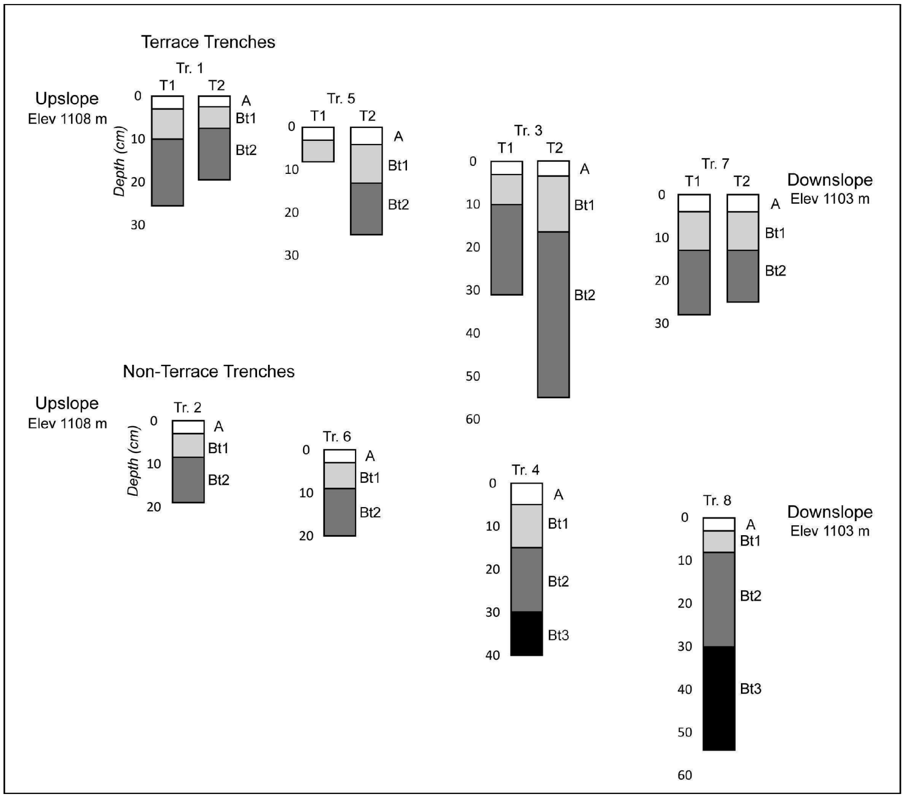


Figure 4.7. Horizons of the Bull Tank trenches. Distance between sample points is not representative.

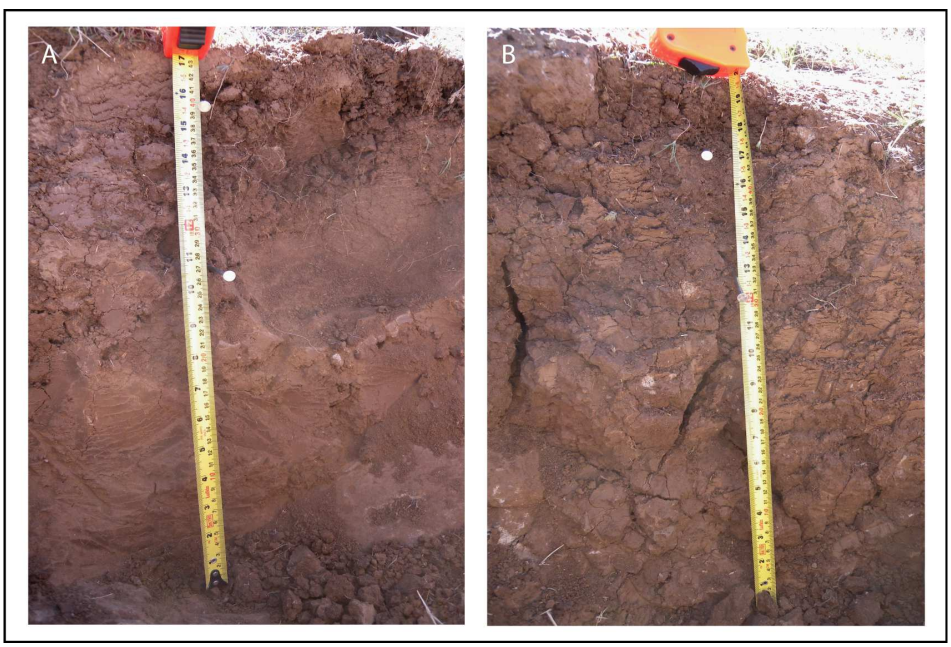


Figure 4.8. Soil profiles of Trench 3, Terrace 2 (A) and Trench 4 (B).

means and standard deviations are presented in Figures 4.9 and 4.10. Paired t-tests were evaluated at 0.05 and 0.1 significance levels.

Bulk density, water holding capacity and clay concentration increase with profile depth, while silt and sand concentrations decrease with depth for both contexts. Terrace A horizons are coarser silt loams compared to finer textured silty-clay non-terrace soils. Bt clay accumulations are slightly lower in terrace contexts, which are identified as a silty clay or clay loam whereas non-terrace contexts were always classified as a silty clay. The higher clay concentrations of non-terrace soils contribute to higher WHC in non-terrace contexts compared to the lower WHC levels of coarser terrace contexts. Terraces likely have fewer visible cracks because soil texture, at the surface and in the subsoil, is coarser compared to non-terrace areas.

Organic matter concentrations are similar between contexts but notably are at their lowest levels in the uppermost Bt strata of terraces. Available P concentrations decrease with soil profile depth. Means for terrace contexts are considerably skewed by high available P values from the relatively shallow Trench 5. Total Carbon and Nitrogen concentrations are similar between terrace and non-terrace contexts, with concentrations in terraces tending to be slightly lower. This difference may be due to the greater abundance of modern vegetation present on non-terrace surfaces. Overall, nutrient concentrations decrease with soil profile depth indicating that most of the nutrients are located in the topsoil rather than sequestered in subsoil, and therefore are more susceptible to erosional loss and transport via surface runoff.

Table 4.2. Descriptive statistics and paired t-test results of physical soil properties for 8 pairs of terrace and non-terrace locations.

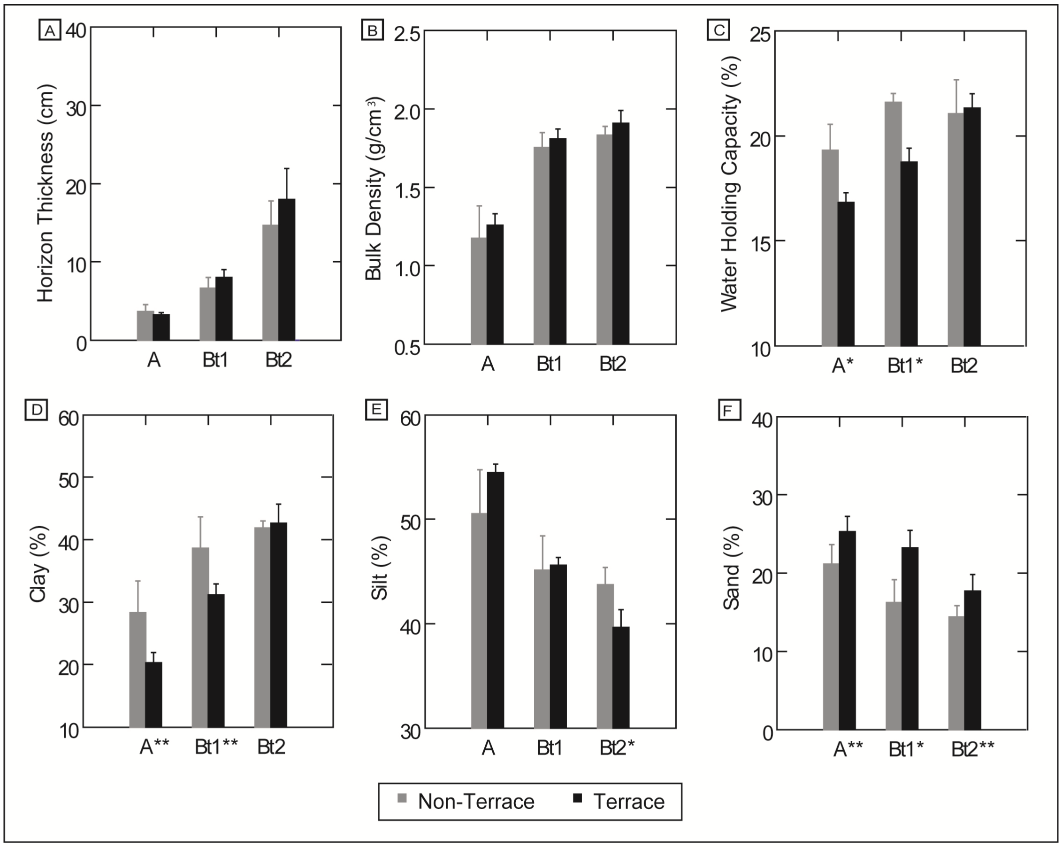
Property	Stratum	Location	Mean	S.D.	P-Value	Significance
Thickness	A	Terrace	3.25	0.76	0.573	
		Non-terrace	3.67	1.16		
	Bt1	Terrace	8.0	2.62	0.179	
		Non-terrace	6.63	2.29		
	Bt2	Terrace	18.0	9.60	0.513	
		Non-terrace	14.63	5.31		
	Bt3	Non-terrace	17.0	9.90		
Bulk Density (g cm^{-3})	A	Terrace	1.26	0.2	0.486	
		Non-terrace	1.17	0.65		
	Bt1	Terrace	1.88	0.23	0.449	
		Non-terrace	1.75	0.13		
	Bt2	Terrace	1.91	0.18	0.509	
		Non-terrace	1.83	0.95		
	Bt3	Non-terrace	1.88	0.11		
Sand (%)	A	Terrace	25.32	5.09	0.079	**
		Non-terrace	21.16	4.15		
	Bt1	Terrace	22.10	5.32	0.019	*
		Non-terrace	16.24	4.88		
	Bt2	Terrace	17.70	5.14	0.097	**
		Non-terrace	14.40	2.41		
	Bt3	Non-terrace	10.87	3.20		
Silt (%)	A	Terrace	58.19	11.69	0.139	
		Non-terrace	50.51	7.05		
	Bt1	Terrace	45.77	2.04	0.738	
		Non-terrace	45.12	5.49		
	Bt2	Terrace	39.65	4.12	0.015	*
		Non-terrace	43.73	2.77		
	Bt3	Non-terrace	45.64	1.31		
Clay (%)	A	Terrace	20.27	4.52	0.087	**
		Non-terrace	28.34	8.49		
	Bt1	Terrace	32.13	4.01	0.060	**
		Non-terrace	38.63	8.38		
	Bt2	Terrace	42.64	7.37	0.731	
		Non-terrace	41.86	1.91		
	Bt3	Non-terrace	43.51	1.31		
WHC (%)	A	Terrace	16.84	1.22	0.038	*
		Non-terrace	19.32	2.07		
	Bt1	Terrace	18.76	1.73	0.002	*
		Non-terrace	21.60	0.71		
	Bt2	Terrace	21.33	1.66	0.790	
		Non-terrace	21.60	2.70		
	Bt3	Non-terrace	21.29	0.95		

*Significant at 0.05, ** Significant at 0.1.

Table 4.3. Descriptive statistics and paired t-test results of nutrient soil properties for 8 pairs of terrace and non-terrace locations.

Property	Stratum	Location	Mean	S.D.	P-Value	Significance
Organic Matter	A	Terrace	4.42	0.83	0.513	
		Non-terrace	4.66	0.81		
	Bt1	Terrace	4.00	0.56	0.005	*
		Non-terrace	4.72	0.08		
	Bt2	Terrace	4.67	0.38	0.471	
		Non-terrace	4.54	0.24		
	Bt3	Non-terrace	4.43	0.01		
Available P mg/kg-1	A	Terrace	31.88	9.18	0.154	
		Non-terrace	27.65	5.72		
	Bt1	Terrace	17.70	9.72	0.249	
		Non-terrace	15.15	5.01		
	Bt2	Terrace	10.14	7.51	0.082	**
		Non-terrace	15.25	2.07		
	Bt3	Non-terrace	1.60	0.00		
Total C g/kg-1	A	Terrace	8.61	1.30	0.498	
		Non-terrace	10.58	3.74		
	Bt1	Terrace	8.15	1.14	0.195	
		Non-terrace	8.03	0.75		
	Bt2	Terrace	9.91	3.75	0.880	**
		Non-terrace	9.00	2.54		
	Bt3	Non-terrace	8.42	1.82		
Total N g/kg-1	A	Terrace	0.84	0.13	0.460	
		Non-terrace	1.02	0.32		
	Bt1	Terrace	0.80	0.09	0.819	
		Non-terrace	0.80	0.07		
	Bt2	Terrace	0.96	0.34	0.320	
		Non-terrace	0.87	0.23		
	Bt3	Non-terrace	0.75	0.16		
C:N	A	Terrace	10.27	0.43	0.919	
		Non-terrace	10.09	0.57		
	Bt1	Terrace	10.16	0.35	0.004	*
		Non-terrace	10.09	0.57		
	Bt2	Terrace	10.31	0.39	0.226	
		Non-terrace	10.29	0.31		
	Bt3	Non-terrace	10.77	0.18		

*Significant at 0.05, ** Significant at 0.1.

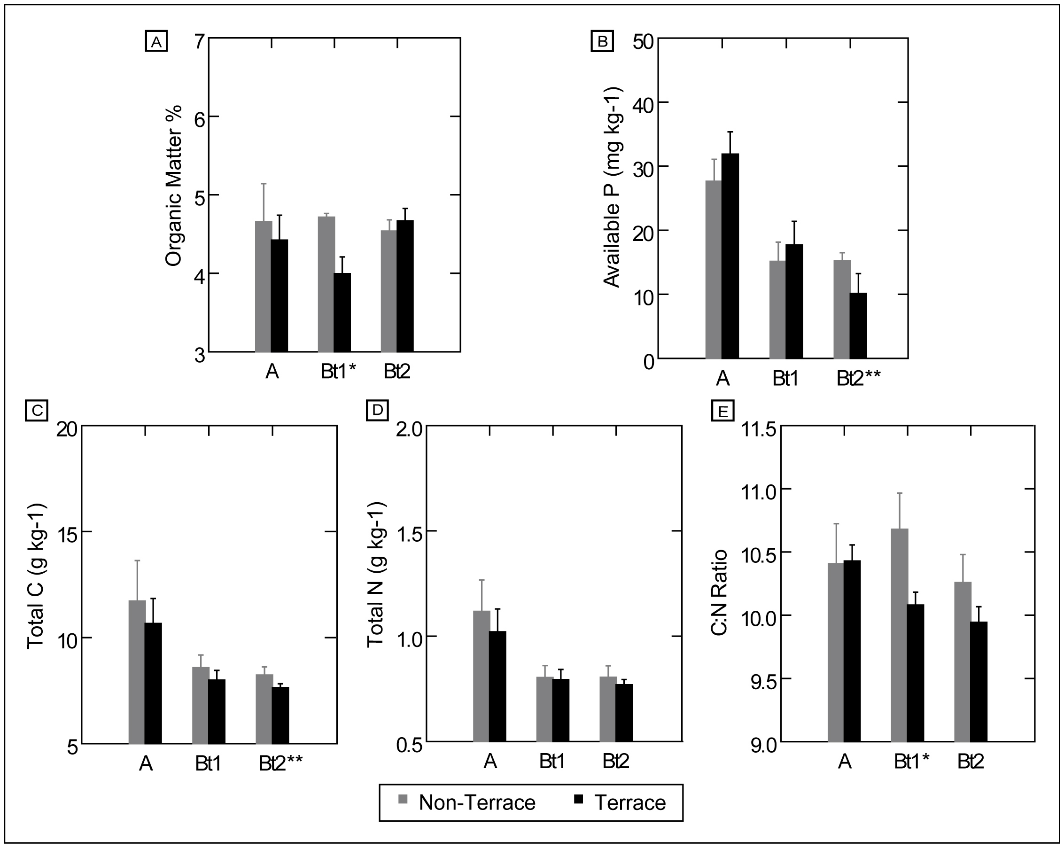


*Significant at 0.05, **Significant at 0.1.

Figure 4.9. Comparison of horizon thickness (A), bulk density (B), water holding capacity (C), and particle size (D-F) between non-terrace and terrace contexts. Bars indicate means and error bars are ±1 standard deviation.

Discussion and Conclusion

There are two major conclusions to draw from comparison of excavated trenches in terraced and non-terraced areas. First, there are subsurface horizon thickness and particle size differences between soils. Contrary to expectations, terrace soils are coarser than and similar in thickness to non-terraced counterparts. These differences are possibly a consequence of differential erosion from surface runoff, an idea expanded upon in below based on data presented in Chapter 6. Second, there are no nutrient differences between the terrace and non-terrace contexts. The lack of nutrient



*Significant at 0.05, ** Significant at 0.1.

Figure 4.10. Comparison of organic matter (A), available P (B) and Total C (C), Total N (D), and the C:N ratio (E) data for non-terrace and terrace contexts. Bars indicate means and error bars are ±1 standard deviation.

differences might be explained by the 700 year absence of farming as well as homogenization from eolian deposition (Nakase 2012) and is similar to other nutrient studies in this landscape (Kruse-Peeples et al. 2010; Spielmann et al. 2011; Trujillo 2011; Trujillo et al. in press). Cultivation did not have long-term consequences for soil fertility in the region that is detectable 500 years after regional abandonment.

Explanation of A Horizon Difference between contexts. In the Bull Tank system, no differences in A horizon thickness of terrace and non-terrace locations were observed with both being a relatively thin, 3-5 cm. Thin A horizons are contrary to the expectation that soil profiles would be thicker behind terrace features as sedimentation occurred over time. Based on soils in other terraced agricultural contexts, thickened A horizons frequently occur due to the accumulation of runoff, stabilization of soil aggregates, and erosion control provided by the terrace features (Goodman-Elgar 2008; Sandor et al. 1986; Sandor 2006). Thickened A horizons are also frequently observed in runoff field locations that do not have terraces but are in relatively flat alluvial fan settings that spread runoff across the field (Homburg et al. 2005). However, the profiles of terrace planting surfaces at Bull Tank do exhibit a characteristic wedge shape with the profile being thickest just behind the terrace feature, a common characteristic of terrace profiles (Sandor 2006).

Many of the rocks used in the terrace constructions currently rise above the ground surface several centimeters rather than being even or flush with the terrace planting surface, as observed from the trench profiles (Figure 4.7). Observations from across the site indicate that it is common for terrace rocks to be 2-10 cm higher than the upslope ground surface. It appears as though sedimentation behind the constructed terraces is not currently occurring within this system; rather erosion is occurring resulting in a lower ground surface compared to terrace rock level and in the lack of expected A horizon thickness. Surface runoff flowing across the terraces in the absence of human management may have caused erosion of these surfaces rather than sedimentation over the centuries since abandonment 550 years ago. The post-abandonment processes such as runoff in the absence of human management or even 20th century cattle grazing are likely to have a more dominant influence on the soil characteristics visible today than prehistoric cultivation.

It is likely that terrace construction and management of this field during prehistoric farming activities built up A horizon thickness by preventing erosion and promoting deposition of sediments and detritus transported by runoff. Rebuilding damaged terraces or augmenting terraces with brush to capture more detritus would have been effective ways to build up the soil. Therefore, the prehistoric agricultural surface was likely once even with the rock level of terraces rather than the surface level we are observing it today because of runoff erosion over the centuries.

Texture differences between terrace and non-terrace A horizons also support an interpretation that terrace surfaces have experienced erosional loss (Table 4.2, Figure 4.9). Terrace A horizon soils are identified as silt loams whereas non-terrace A horizon textures are silty clay loams. The greater coarseness of soil texture in terraces is likely due to the removal of fine sediments, particularly clay, which are preferentially transported during runoff events as discussed in the following chapter (Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Parsons et al. 1991). It appears that there is on-going translocation of fine sediments downslope via surface runoff leading to overall coarser soil textures in terrace contexts[1]. Terrace contexts might have had similar textural qualities to non-terraces originally. What is unclear at this time is if this loss of fine material is related to the period of cultivation or if it is a consequence of terrace abandonment.

Explanation of the lack of nutrient differences between contexts. Given the details of previous nutrient studies in the region (see Kruse-Peeples et al. 2010; Nakase 2012;

Spielmann et al. 2011; Trujillo 2011), the absence of significant nutrient differences between terraced and non-terraces contexts within the Bull Tank area is expected. The lack of differences is interpreted to indicate that either farming the terrace soil had no long-term nutrient impacts or that any differences that did exist were evened out in the ensuing 550 years. Nakase (2012) has argued that the lack of difference between contexts is due to continual dust deposition causing homogenization of surface soils.

The growing body of studies focused on prehistoric farming indicates a high degree of variability in the types of long-term impacts to soils and includes examples of degradation, minimal net change, and enhanced soil quality (Homburg and Sandor 2011). These data from runoff agricultural terraces in the Bull Tank area, and Perry Mesa more broadly, indicate minimal net change to the nutrient characteristics of soils. The lack of nutrient differences observed in the data from the trench excavations is used as justification to utilize modern soil nutrient data as a proxy for prehistoric conditions.

Linking Soil and Terrace Field Conditions to Agricultural Productivity

Soil, including the individual soil particles and their interrelated profile characteristics, is an integral component of agroecosystems. Soil provides the context for seed germination and plant growth – water, nutrients, and structure. The soil of Perry Mesa runoff fields is adequate for crop production, but may have presented many challenges as well.

The soil profile depths of Perry Mesa soils are relatively shallow, limiting the space for plant roots to expand to acquire nutrients and moisture. Limited soil volume to acquire these resources can ultimately influence yield. For example, recent simulations of ancient maize productivity in other dryland Southwestern contexts showed a loss of 13%

of available organic N in simulations using a profile depth of 50 cm compared to those using 100 cm, implying a loss to yield (Benson 2011a, b).

Deep planting maximizes available water stores for the early development of the plant allowing for earlier planting and maximizing limited water. Deep planting was a common strategy used by traditional Southwestern farmers to prevent damage from spring frosts but is also advantageous for accessing moisture (Hack 1942; Hill 1938; Muenchrath et al. 2002). The relatively shallow soils of Perry Mesa would make deep planting to a depth of 25 cm difficult to impossible. Planting depth on Perry Mesa, therefore, would have been much shallower and in soils that would be more susceptible to dry conditions.

Bull Tank profiles described here rarely extended beyond 50 cm and were frequently 20-30 cm in depth before C horizon was encountered. Even with surface erosion argued for above, profile depths likely were an additional few cm deeper during management of the system.

A horizon thickness was only 2-5 cm in all contexts from Bull Tank. For comparison, A horizons are between 20 to 25 cm thick in modern, valley margin fields at Zuni (Homburg et al. 2005: Figure 5) and 10 to 30 cm thick within prehistoric upland terraced fields of the Sapillo Valley of southwest New Mexico, despite experiencing accelerated erosion during prehistory and over the centuries since abandonment (Sandor et al. 1990:79). Investigations of a productive modern Hopi field revealed a profile depth of 100 cm (Dominquez and Kolm 2005:751). These soil profiles are all deeper than those recorded on Perry Mesa and would provide sufficient soil volumes from which cultigens could exploit nutrients and moisture.

To overcome this limitation, Perry Mesa farmers likely used specific cultigen varieties adapted to profile depth conditions. In Hopi sand dune fields, farmers utilize a variety of maize that has a single radicle root that extends deep into the ground to take advance of deep soil moisture (Bradfield 1971). Perry Mesa farmers in contrast, would likely have planted maize varieties that promoted seminal root growth to expand the region of moisture uptake laterally, influencing the density of plants. Relatively shallow soils may have also promoted other crops, such as beans or little barley, which are not as tall as corn and may require less rooting space.

Terraces have a more favorable soil texture for agriculture compared to non-terraces. Historic and contemporary southwestern farmers prefer soil profiles that have coarse-textured sandy surface layers that have more fine-grained loam or clayey horizons underneath which promotes rapid infiltration and moisture retention (Bradfield 1971; Dominquez and Kolm 2005; Hack 1942; Cushing 1920; Muenchrath et al. 2002). Textures ideal for agriculture are loam or silt loam with clay content increasing with depth. Clay conditions should not be so high that water logging or anoxic conditions develop (Gliesman 2007; Olson and Sander 1988). Soils from Bull Tank are silt loams transitioning to clay loams with depth. Terraces have slightly lower clay content than non-terraces. Soil samples from other Perry Mesa agricultural contexts also indicate that terraced locations trend towards a loam, or coarser, textures compared to non-terraced soils (Kruse-Peeples et al. 2010; Spielmann et al. 2011).

In terms of some soil nutrient conditions, Perry Mesa agricultural soils do not appear to be a challenge for farming the region. Nakase (2012) concluded that phosphorus would not have likely been depleted during the course of the 150 year period of intensive occupation of the region and is not a current concern for the area based on soil collections from the La Plata area. Nitrogen availability, however, likely was a concern and will be addressed in subsequent chapters.

Carbon and nitrogen nutrient concentrations on Perry Mesa are similar to other cultivated regions of the southwest. For example, average total organic carbon concentrations from the top 15 cm of intensive fields are 11.28 g/kg and total nitrogen concentrations are 0.87 g/kg (Homburg et al. 2005: Table VI). Bull Tank A horizon total nitrogen and carbon concentrations are 0.84 and 8.61 g/kg respectively, a similar range to the Zuni results where traditional maize farming is still practiced.

Chapter 4 Notes

[1] Data supporting this hypothesis is presented in Appendix C based on the runoff collection study discussed in Chapter 6.

Chapter 5:

SOIL MOISTURE CONDITIONS OF THE PERRY MESA RUNOFF AGROECOSYSTEM

This chapter addresses water availability within the soils of the Perry Mesa agroecosystem. Water, in addition to nitrogen, is the primary limiting factor for plant growth, particularly in arid and semi-arid regions. Specifically two questions are addressed: 1) Does soil moisture differ between terrace and non-terrace soils in this agroecosystem; and 2) given the rainfall dynamics of central Arizona, what is the likely timing of planting in the region? As presented in chapter, 4, soil texture and nutrient properties differed between terraced and non-terraced soils. This chapter addresses how these differences relate to moisture availability for crops. These issues are significant in understanding this prehistoric agroecosystem because they can determine the extent that human manipulation and decision making can influence productivity. Understanding the timing of agricultural planting is also useful in determining the options available to farmers in this landscape and what constraints they may have been experiencing.

Fluxes of soil water content were measured *in situ* and logged in real-time. Integration of real-time precipitation data allowed for descriptions of how soils respond to precipitation events of different intensities and depths over time. The amount of water in a soil is affected by natural factors, such as topography, primary productivity, texture and rock content, structure, climate, precipitation intensity; and management factors, such as runoff capture with terraces, tillage, mulching, and maintenance of ground cover. All of these factors are interactive and their net effect changes across time and space. The monitored soil conditions are considered to be a proxy for prehistoric conditions.

Terraces would have been maintained and managed prehistorically, likely leading to better water capture.

Results indicate that the terrace soil profiles have higher soil water content and retain soil moisture for longer periods of time than in non-terrace locations, increasing the productive capacity of the agroecosystem in terraced locations. Planting was possible in the area when temperatures increased in April but it is unclear if there would have been enough moisture to both facilitate seed germination and sustain the plants until the summer monsoon rains in late June or early July. Observations indicate that it would be risky to plant in the spring and soil moisture would likely be too low. Alternative strategies such as focusing on spring crops such as little barley and alternate resources such as agave are addressed.

Methods and Procedures

Soil water content was monitored *in situ* under natural rainfall conditions to compare moisture fluxes under different precipitation events and between terraces and non-terraced soil profiles. Volumetric water content was measured at two depths in the soil profile (7 and 20 cm) over the course of 21 months. The measurement of soil moisture fluxes *in situ* allows for detailed monitoring of soil water content and transfer in real-time at a relatively low cost and labor effort. This type of monitoring also allows for data monitoring at a temporal scale that would be impossible with destructive soil collection such as periodic sample collection and lab analysis.

In situ volumetric water content (VWC) of the soil was monitored using two types of sensors, the EC-TM (now called 5TM by the manufacturer) and the 5TE. Sensors and data processing software are manufactured by Decagon Devices, Inc. (Pullman, WA).

The sensors consist of prongs or tines inserted into undisturbed soil. The sensors measure the dielectric constant of the soil, an electrical property that is highly dependent on moisture content. Calibration equations correlate the dielectric content with soil moisture. The calibration equation applied to the sensor output was the default equation given by Decagon Devices developed for generic mineral soils based on the Topp et al. (1980) equation. This results in approximately ± 3% accuracy for most mineral soils (Decagon Devices). Each sensor has a 0.3 L volume of influence.

Sensors were connected to an Em50 datalogger (Decagon Devices, Pullman, WA). VWC (m^3/m^3), T (°C), and raw, unprocessed dielectric constant data were collected and stored every 10 min. The 5TE sensors also collected bulk electrical conductivity (EC; dS/m) measurements. After some initial experimentation with the 5TE sensors it was determined that the additional electrical conductivity reading was not required and difficult to accurately attain in the high clay soils on Perry Mesa. The second group of sensors was the EC-TM variety that collects only VWC and T data because of the cost savings. Data were downloaded manually during each field visit, at least once every 5 weeks. Post-field data analysis included temperature sensitivity correction using multiple regression analysis (Cobos and Campbell 2007).

Four 5TE sensors were installed at the downslope location and four EC-TM sensors were installed at an upslope location with one terrace and non–terrace pair each in upslope and downslope locations (Figure 5.1). Each set included 2 sensors installed within the profile of a terrace planting surface at a depth of 5-7 cm, referred to as the upper profile sensor, and 17-20 cm, referred to as the lower profile sensor. The depth of the sensors is given as a range because of the width of the sensors prongs and the sensor volume of influence. Similarly, 2 sensors were installed at the same depths within a profile of a nearby non-terraced area for upslope and downslope locations. Locations for the terrace sensors were selected in areas were the features were intact (no stones washed away) and were in proximity to an area with no evidence for a terrace feature or planting surface. Soil moisture sensors were located in the vicinity of trench excavations (Chapter 4) and runoff collection units (Chapter 6) but were not within the same terrace features.

The upper profile sensors were installed just below a granularly structured A horizon and the lower profile sensors were installed in lower strata of the Bt horizon, a clay-rich horizon with high bulk density and a clay content that increased with depth (Figure 5.2). Horizon details of the Bull Tank field system are described in Chapter 4. Generally, the terrace location soils were coarser than non-terrace locations. Rock fragments were restricted to the ancient terrace features themselves as opposed to being distributed throughout the profile. Non-terrace bulk densities were higher, particularly for the Bt2 strata, and rock fragments were more frequently located on the surface and within the soil profile compared to the terrace locations. Subsurface terrace soil structure was generally weaker, forming granular or blocky aggregates. Non-terrace Bt horizons generally exhibited a stronger structure. The material was a coherent mass, lacking formation into aggregates.

The installation procedure began by hand excavating a trench approximately 25 cm wide and 30 cm deep in each location. Sensors were installed at 5-7 cm and 17-20 cm depths in the undisturbed wall of the trench. Sensor prongs were placed perpendicular to the ground surface per Decagon Devices' installation procedures. Sensors installed at different depths were not installed directly above one another but rather in opposite sides

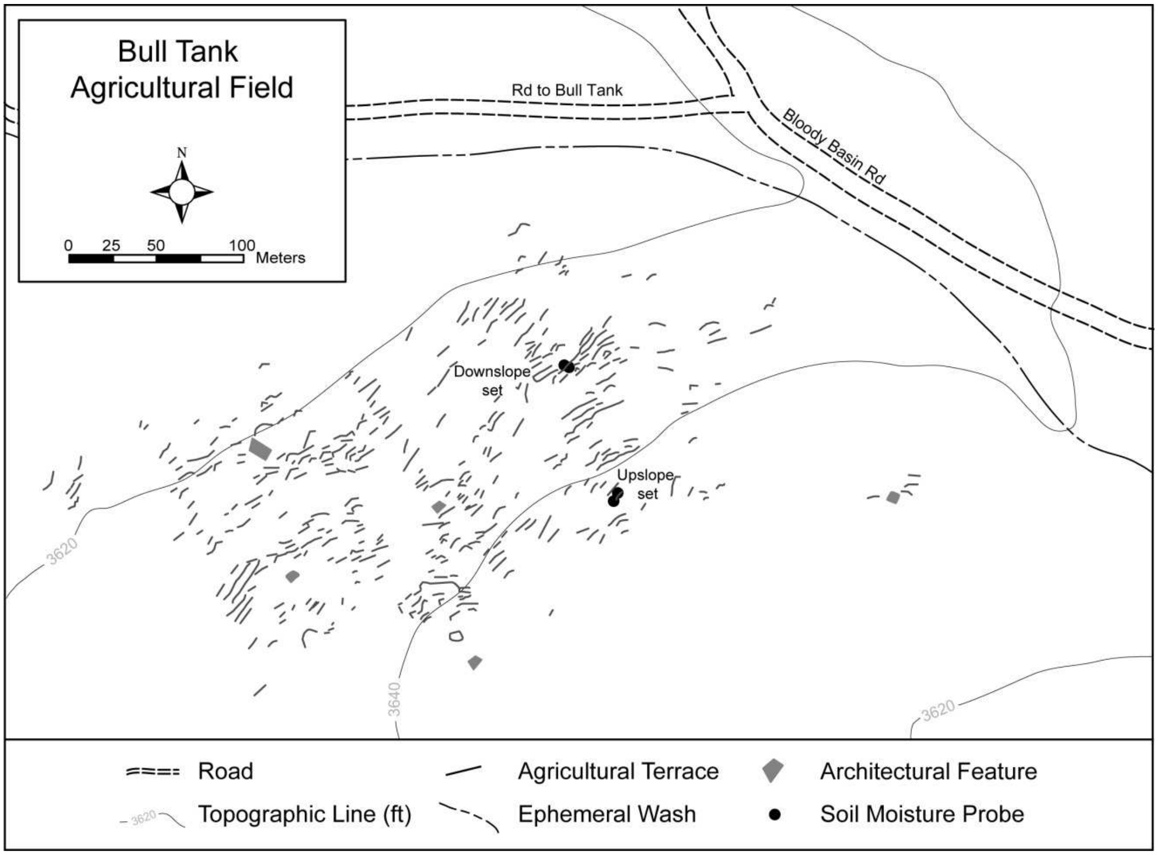


Figure 5.1. Location of soil moisture probes within the Bull Tank Agricultural Field.

of the trench to minimize interference. The sensor wires were run horizontally away from the sensor head and tines to minimize the creation of a preferential flow path. The trench was refilled and tamped down to avoid creation of preferential flow paths. Cracks formed by clay shrinkage and old root channels were avoided as these features may serve as preferential flow paths.

At the time of installation, the soil was recently wetted, easing insertion of the sensor prongs, and good contact with the soil matrix was obtained. Experimentation with the sensors during dry conditions made installation very difficult. Soil clods would break apart when prongs were installed, creating air and potential water pockets. When sensors

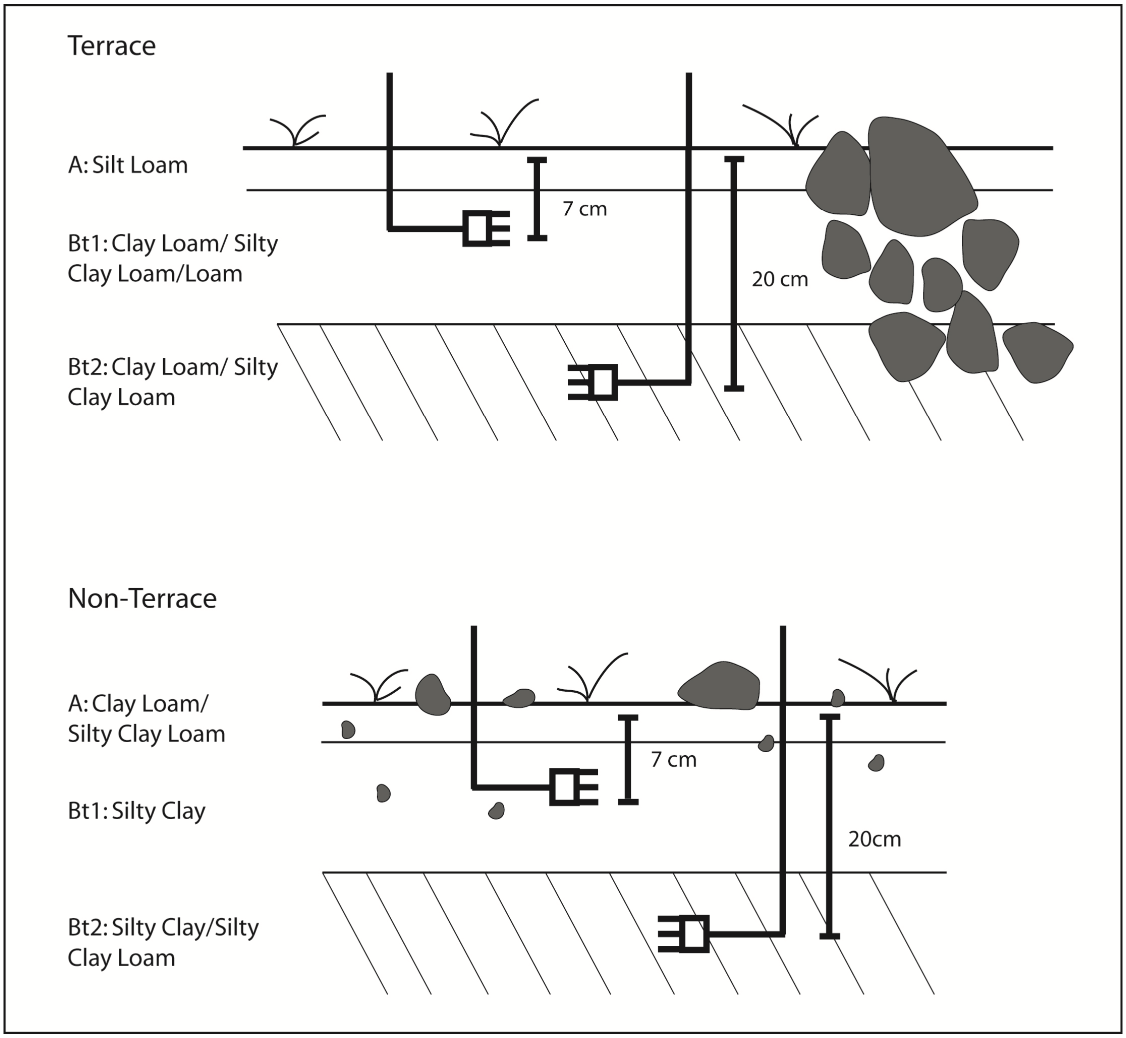


Figure 5.2. Schematic representation of soil profile characteristics of terrace and non-terrace soil moisture probe locations.

were removed at the end of the observation period, good contact between the soil matrix and the sensor prongs was still evident. Care was taken to ensure all of sensors were installed similarly so that the results could be compared with confidence.

Collection Periods. Not including a period of initial experimentation, sensors were installed in on December 31, 2009 and they collected data continuously until October 3, 2011 for a total of 21 consecutive months. Occasionally, a sensor was not functioning due to connection loss between the sensor cord and the data collector due to rodent disturbance along the cord, not to an issue near the sensor prongs. The figures (Figure 5.3; Figure 5.4) mark these periods with an absence of data for that sensor. The sensor was removed for repair at a time when the soil was dry (early April 2010) and reinstallation was difficult and was attempted several times. Care was taken not to disturb the lower profile sensor when the upper sensor was removed. Good contact between the soil matrix and the sensor prongs was not achieved until the end of the 2010 monsoon season.

Precipitation Conditions. Rainfall data were collected with a digital tipping bucket rain gauge installed in the southwestern portion of the Bull Tank Agricultural Field (Campbell Scientific Inc., precision 0.2 mm). Rainfall totals were recorded at 1 minute intervals during the summer monsoons and 10 minute intervals during the winter because field visits for data downloading were less frequent. The frequency of measurements allowed for calculation of rainfall intensity for each storm on a standardized scale (mm/hr) and determination of the duration (minutes) and depth (mm) of individual rainfall events.

Winter 2010 was heavily influenced by wet El Niño conditions and there was 289.2 mm (11.38 in) of precipitation during the Jan- March period. Winter 2011 was heavily influenced by La Niña conditions, leading to drier than average conditions (CLIMAS 2011). It rained a total of 56.6 mm (2.23 in) from Jan-March in 2011. A few small spring precipitation events occurred in April – May, 2011 (15 mm, 0.59 in).

Summer monsoons in 2010 were drier-than-average (CLIMAS 2010b) producing 117.6 mm (4.62 in) and the season did not begin until mid-late July. Several summer

2010 events were of high intensity and high volume producing runoff. The 2011 summer period was also drier than average (CLIMAS 2011) producing just 53.4 mm (2.1 in) and the season began in early July. Sensors were removed in early October 2011. No summer 2011 precipitation events at Bull Tank were high in volume or intensity typical of summer monsoon storms. Based on runoff collection results from 2010, it is estimated the July 5 precipitation event would have produced the only substantial runoff event during the entire 2011 summer monsoon.

Because 150 mm (6 inches) growing season precipitation is generally considered the lower limit for modern maize without the use of irrigation (Shaw 1985), it is unlikely that the rainfall conditions of the 2010 season at Bull Tank would have produced a viable yield, although terraces did have higher moisture retention as discussed below. The dry 2011 conditions would have likely resulted in a total crop failure.

Each sensor location responded differently to precipitation events due to the sensor type as well as the variability in soil conditions and depth of the sensor. The upslope sensors exhibit more extremes in soil water content than downslope sensors. The upslope sensors are EC-TM sensors and the downslope sensors were a different sensor model, the5TE; both models measure the same variable, VWC. The difference in readings is likely related to the sensitivity of the sensors and absolute comparisons between upslope and downslope readings are not attempted.

Results and Discussion

Soil moisture observations indicate that small rainfall events in the area (<3 mm, 0.12 in) are likely to have no influence on soil moisture at a depth of 7 cm and it takes a moisture event of >10 mm (0.39 in) to reach to lower depths of 20 cm (Figures 5.3 – 5.6).

This pattern has been shown in other arid and semi-arid Southwestern environments (Adams et al., 1999; Farquharson et al., 1992; Goodrich et al. 1995; Shreve 1934).

A prolonged soil moisture increase at the lower profile depths in either context was only achieved during the winter of 2010, a very wet season attributed to above normal El Niño cycle precipitation. Based on soil investigations in southeastern Arizona, soil moisture infiltration beyond a 30 cm depth is infrequent during the summer monsoon and most likely occurs only during winter regimes influenced by El Niño conditions (Scott et al. 2000). In the Bull Tank location, the observed summer monsoons did register soil moisture at the monitored 20 cm depth and after large storms very high moisture content, particularly in the downslope location terraces in 2010 (Figure 5.6).

Just below the surface to 20 cm is where a majority of maize roots will be located, it is important for moisture to be maintained at this depth. Wetting of surface soils only has a fleeting effect. Even relatively quick succession of numerous small events (3-10 mm) in the summer, as was the case in 2011, also had little or no impact on soil moisture at lower depths. It is inferred that these small events, even though frequent, have little impact on crop roots.

Terrace Effects on Soil Water Content

The main purpose of the soil moisture monitoring was to determine if terrace soils provided any soil moisture advantages over non-terrace locations. Snapshot views of the monitoring results indicate that terrace soils register the highest moisture readings based on the peaks in the graphs (Figure 5.3, 5.4) particularly during the summer monsoon periods (Figures 5.5, 5.6). Terraces have relatively higher moisture levels, quick increases in water content, and prolonged periods of higher water content within

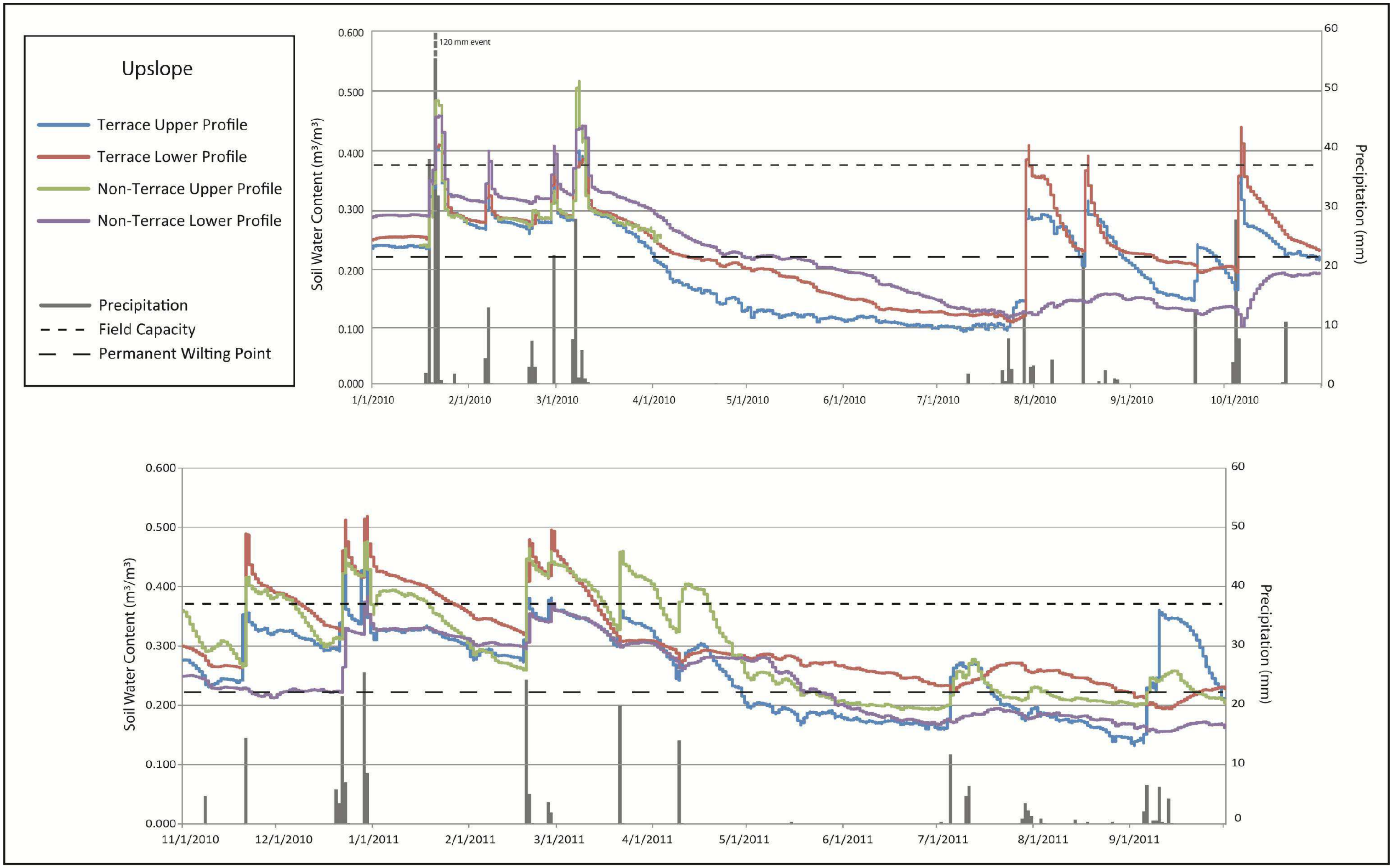


Figure 5.3. Soil water content for upslope set from Jan 1, 2010 – October 3, 2011.

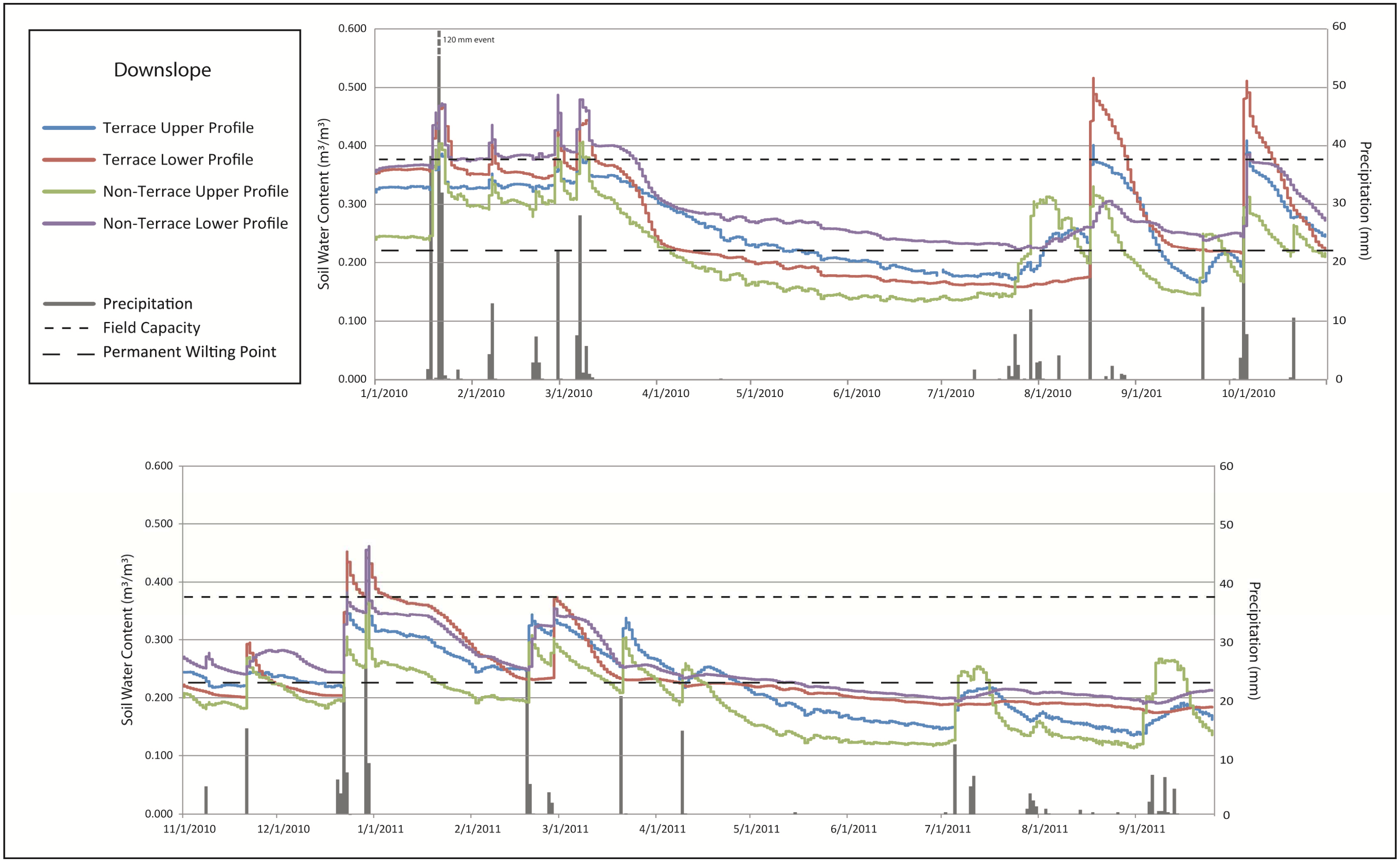


Figure 5.4. Soil water content for downslope set from Jan 1, 2010 – October 3, 2011.

the lower profile sensors compared to non-terraces (Figure 5.5, 5.6). These differences are most pronounced for the bottom sensors in the upslope location but the top sensors of the downslope locations. Differences between terrace and non-terrace locations were not pronounced in a wet winter season (2010) possibly indicating that soil water differences are homogenized when water is abundant.

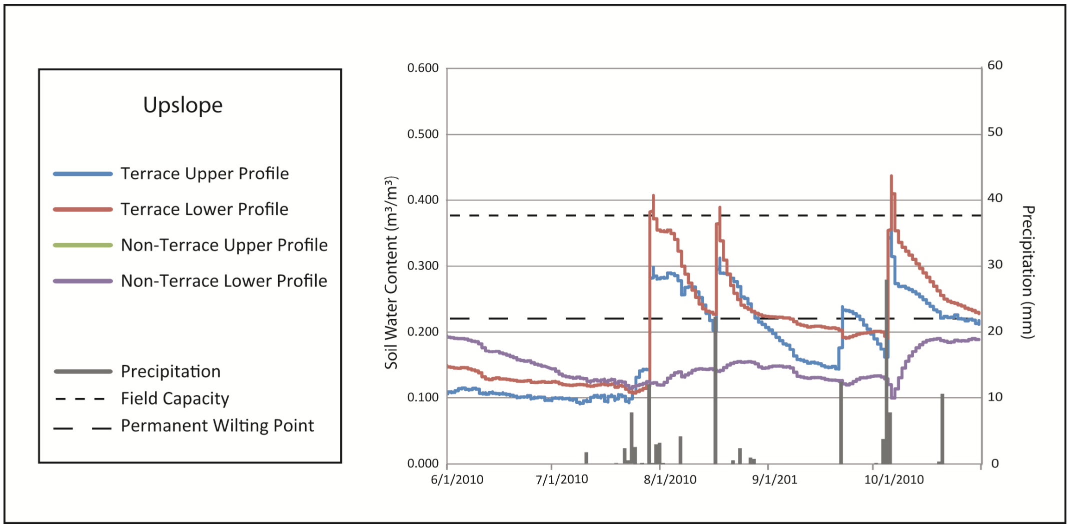


Figure 5.5. Volumetric water content for upslope set from June 1, 2010 – October 31, 2010.

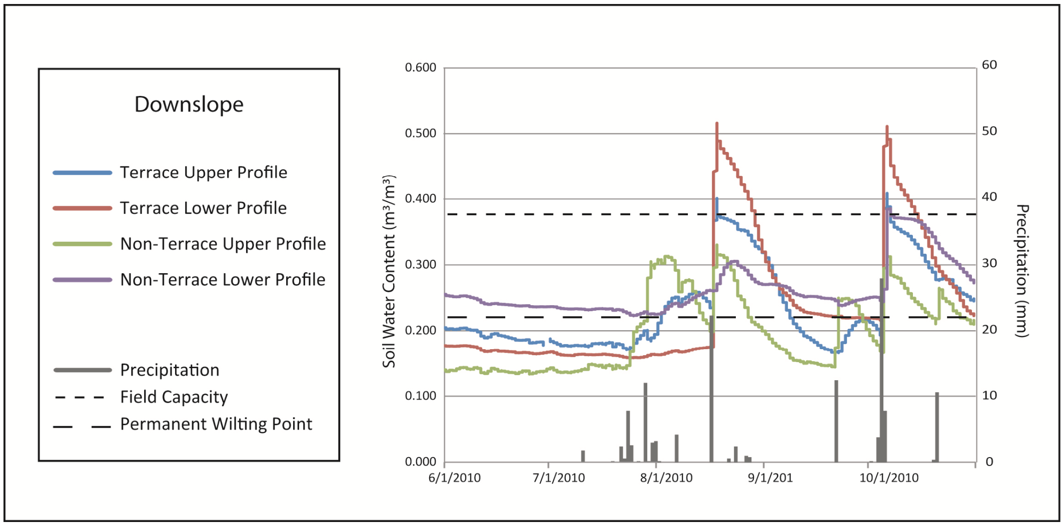


Figure 5.6. Volumetric water content for downslope set from June 1, 2010 – October 31, 2010.

The in-situ monitoring provided by the soil probes allows for examination beyond snapshot or momentary views of soil moisture. Two long-term temporal scales of analysis were undertaken to determine if terraces have higher soil water content. The first examines the proportion of time that terraces register equal or higher moisture content than non-terraces for each season (Table 5.1). The second analysis compares the moisture content of terraces and non-terraces for a 5 day period after larger rain events (Figure 5.7). Based on the examination of periods immediately after large rainfall events it appears that terraces have higher overall soil moisture compared to non-terraces. The long-term trends however are more equivocal and it is unclear if terraces retain moisture longer than non-terraced locations.

Examination of the entire period of observation indicates that terraces register higher moisture content during only some seasons and some contexts, such as the top profiles of the downslope location and the bottom profiles of the upslope location during the summer months (Table 5.1). However the patterns are not sufficiently clear-cut to draw a conclusion that terraces offer higher moisture content compared to non-terrace locations. Ultimately it is the long-term retention of soil moisture that is important for crop growth, particularly at lower depths during summer months. It appears that only the upperslope terrace context provides this advantage with this particular observation period, which was over two dry monsoon periods and a particularly active winter season in 2010. The hypothesis that terraces offer advantages over non-terraces in terms of soil moisture needs further evaluation and data from more sampled areas and weather conditions less extreme than those experienced during this study.

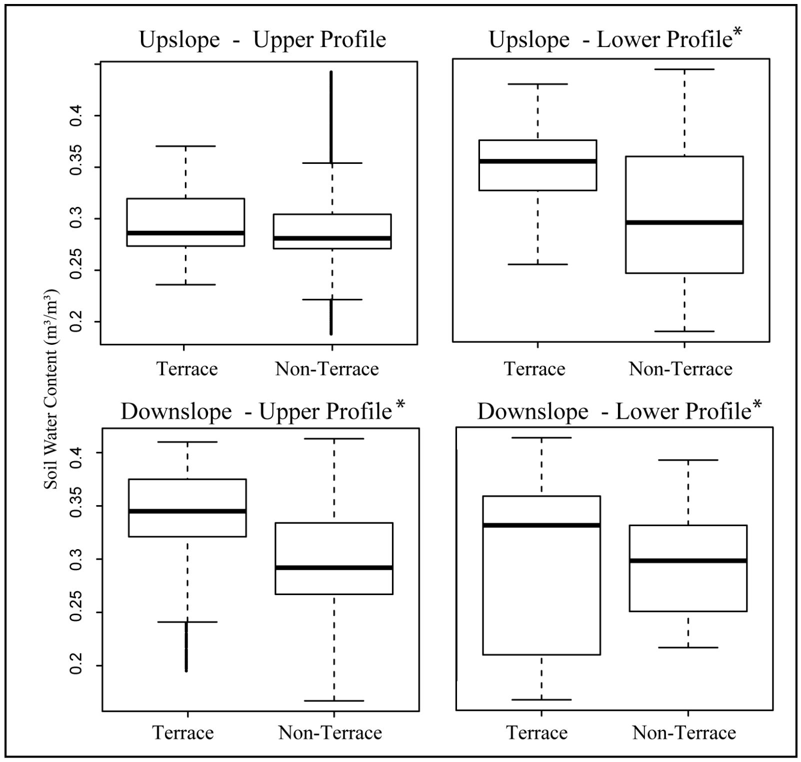
Table 5.1. Comparison of terrace and non-terrace soil moisture for upslope and downslope locations.

Upslope Set				
Season	Dates	Total Number of Days	% of Time Terrace Moisture ≥ Non-Terrace (Upper Probes)	% of Time Terrace Moisture > Non-Terrace (Lower Probes)
Winter 2010	1/16/2010-4/3/2010	78	35.1	0.5
Spring 2010	4/15/2010-6/30/2010	77	NA	0
Summer 2010	7/1/2010-10/31/2010	123	NA	77.7
Winter 2011	11/1/2010-4/15/2010	166	9.3	100
Spring 2011	4/16/2011-6/30/2011	77	0	100
Summer 2011	7/1/2011-10/1/2011	93	33.6	100
Downslope Set				
Season	Dates	Total Number of Days	% of Time Terrace Moisture > Non-Terrace (Upper Probes)	% of Time Terrace Moisture > Non-Terrace (Lower Probes)
Winter 2010	1/1/2010-4/15/2010	104	93.7	3.4
Spring 2010	4/16/2010-6/30/2010	77	100	0
Summer 2010	7/1/2010-10/31/2010	123	79.4	24.2
Winter 2011	11/1/2010-4/15/2011	166	96.4	31.8
Spring 2011	4/16/2011-6/30/2011	77	100	0
Summer 2011	7/1/2011-10/1/2011	93	69.6	0

Examination of the periods immediately after intense rainfall events, in contrast, reveals a stronger pattern with the tendency for terrace contexts to register higher moisture. Soil moisture content of terrace and non-terrace locations were compared for an arbitrarily determined 5 day period after all rainfall events larger than 20 mm (0.78 in; Figure 5.7). A total of 9 rainfall events greater than 20 mm occurred during the observation period, 7 during the winter and 2 during the summer monsoon. These same events produced runoff (see Chapter 4). In three of the contexts, upslope lower profiles and both downslope contexts, terraces have significantly higher moisture content following large rain events ($p<0.001$) based on two-sample t-tests of the VMC. The mean terrace moisture was slightly higher than non-terraces in the upper profiles but the overall relationship was not significant ($p=0.92$). This upper profile comparison for the upslope location did not include large summer rainfall events, however, due to the data gaps from nonfunctioning probes.

The higher and in some instances prolonged soil moisture content on terraces compared to non-terrace locations, particularly after large rainfall events, is likely related to soil texture, structure, the terrace feature, and the higher likelihood of runoff flow across terraces. The surface soils are coarser, bulk density is lower and structure is more granular within terrace locations compared to non-terrace locations which have higher clay content, higher bulk density, and soils are arranged in a more unconsolidated mass as depth increases. Therefore, infiltration is expected to occur more quickly in terrace locations. The slightly coarser surface characteristics of terrace soils allow for quicker infiltration to deeper depths decreasing the loss of water to evaporation.

The percolation of soil water deeper in the soil profile is important during the warm conditions of the summer, which can readily evaporate water near the surface. The looser organization of soil aggregates in terrace soils provides more open pore spaces for



* Significant at <0.001.

Figure 5.7. Box plots comparing soil moisture content of terraces and non-terrace profiles for a 5 day period after large rain events (>20 mm).

water to be transported. The characteristics of the Bt horizon in non-terrace locations essentially prohibit downward infiltration into deeper layers. Water will flow laterally, a process called through-flow, eventually flowing downslope by gravitational forces rather than percolating to lower profile depths. This explains why the lower profile of non-terrace locations rarely had an increase in water content, or had a much delayed response compared to terrace locations, which experience a quick moisture increase after the upper profile sensor responds to the precipitation event. Essentially water is draining quickly downward or vertically within terrace soils but flowing laterally or horizontally above the deeper soil horizon within the non-terrace soils.

The behavior of subsurface water flow is also different in terrace locations because of the presence of the terrace feature itself. As demonstrated with trench excavations (Chapter 4), terraces in the Bull Tank field often have large subsurface rocks incorporated into their construction. Subsurface rocks are much less common in non-terrace locations. Essentially a surface to subsurface wall is present in the soil profiles of terraces keeping the water from flowing downslope within the profile. This wall is not completely impervious but does allow for water to remain within the terrace for extended amounts of time compared to non-terrace locations which lack this barrier to subsurface flow. Terraces thus account for why subsoils retain moisture for longer periods.

Another mechanism that explains the greater moisture in terraces is the presence of more water than simply precipitation alone. As argued in Chapter 6, terrace locations experience more frequent and more abundant runoff during summer rainfall events. Therefore, terrace locations have the potential for more water available for potential infiltration due to the greater amount of runoff flowing across these locations. Runoff is likely generated from the terrace surfaces themselves but is also coming from other surfaces where precipitation exceeds infiltration such as the non-terrace surfaces, which do not have quick infiltration to deeper layers, and rocks within the field system, which are not absorbing large amounts of rainfall. The precipitation not absorbed into the soil creates the surface runoff which flows across terraces, increasing the amount of moisture that can infiltrate and percolate down within the soil profiles. The terrace features are designed to slow this runoff to allow it more time to infiltrate in the soil. The rocks of the terraces themselves are an impervious surface layer that promotes runoff flow to the terrace surface immediately below.

The possible processes explaining why terraces might have more soil moisture than non-terraces are described in Figure 5.8. Precipitation more quickly infiltrates terrace soils, especially the deeper layers because of the terraces tend to be more granular soil structure, coarser texture, and lower bulk density. The rocks of terraces slow soil water movement downslope by creating a semi-pervious subsurface wall. This subsurface wall is not present in non-terraces so water has less time to infiltrate to deeper soils and less time to be available for plants before throughflow processes move water downslope. Infiltration capacity and percolation depth are reduced in non-terrace soils likely because of the A horizon texture and the impervious nature of Bt horizon soils. Additionally, terraces may receive more overall water because of increased amounts of runoff (Chapter 6). Runoff is generated when a portion of rainfall does not infiltrate non-terrace and terrace soils but perhaps more importantly because the abundance of rocks concentrated in the terrace features increases runoff flow to the terrace surface immediately downslope.

Soil Moisture and Agricultural Planting

Moisture was not maintained in the soil during the winter despite high precipitation. Soil moisture did not return until additional precipitation came with the summer rains. Spring planting is common among groups on the Colorado Plateau (Bradfield 1971; Cushing 1920; Hack 1942). Colorado Plateau farmers could take advantage of spring moisture remaining after winter precipitation, including snow melt (Van West and Greenwald 2005, Benson 2011b), to plant in the spring. In contrast, groups who dry-farmed in the Sonoran Desert, who had no winter soil moisture reserves

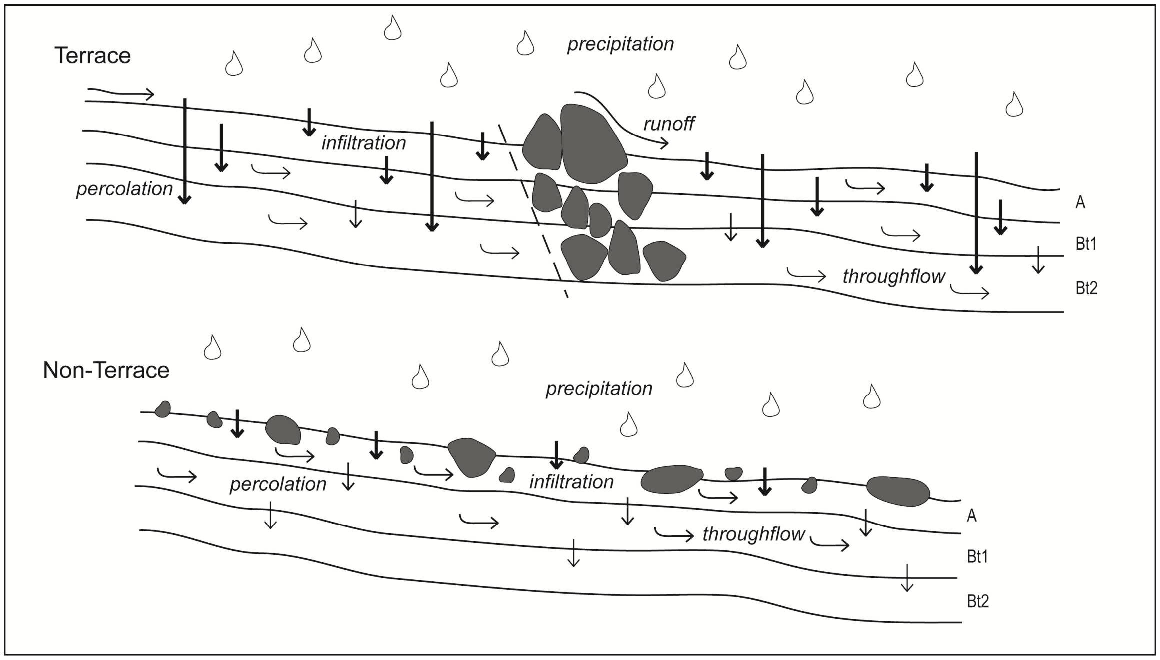


Figure 5.8. Schematic representation of water flow in terrace and non-terrace soil profiles. Length and thickness of lines represent relative relationships of infiltration capacity and percolation depth.

available to water crops, delayed planting until the arrival of the summer monsoons in late June (Castetter and Bell 1942:133-131; Nabhan 1983:68-77). Farmers in the Perry Mesa region would have likely waited to plant most of their crops until the start of the summer monsoon, similar to Sonoran Desert dwellers.

For the years observed, winter soil moisture conditions were often high. The Bull Tank data indicate that during the winter of 2010 (Jan-March), soil water content was always above the permanent wilting point (PWP) and often near or above field capacity (FC), particularly for the downslope location (Figures 5.3, 5.4). The PWP and FC for silty clay loam, the dominant texture for lower profile depths within the Bull Tank Agricultural field, are shown on the graphs for context (See Appendix B). The range of soil moisture between a soil's FC and PWP is the amount of water available for root uptake; moisture levels above or below this range are either too wet or too dry for growth and plant survival.

The Winter 2010 pattern signifies that the soil was very wet, often too wet creating anoxic conditions for plant growth. The abundant rainfall and relatively quick succession of rainfall events left very little time for soils to drain or dry. At the time, it was very difficult to walk without sinking into the ground or to move given the amount of soil sticking to our feet when in the field. Precipitation conditions were very different during the winter of 2011 where rainfall was only 20% of the winter 2010 total. Sensor response, however, also indicated that water content was high during winter 2011 and reached above FC in several instances. Although the overall precipitation amounts were different, the rainfall pattern of light rainfall spread over many hours was similar. Winter rainfall in the southwest has the types of long duration precipitation events that led to deep soil saturation.

During the months of April-June, after the winter rains were over and before the summer monsoon, soil moisture was very low for both years observed. Regardless of whether it was an extremely wet winter (2010) or a relatively dry winter with a few early spring events (2011), soil water content was below or approaching the PWP at the beginning of June (Figures 5.3, 5.4). The wilting point was reached or exceeded in all but two of the 8 observations: the downslope non-terrace profile in 2010 and the upslope terrace lower profile in 2011. In other words, most of the observed locations or periods would not have had enough moisture for seeds planted in the spring (late April or May) to be sustained until the summer rains. Spring planting was possible, but very risky.

It was not until the onset of summer monsoon precipitation that soil moisture increased, and only in some of the contexts did moisture rise above PWP for the period observed. Unfortunately, neither the 2010 nor 2011 summer monsoons were very productive. Moisture levels in both locations failed to be sustained above PWP for any meaningful duration. However, if a summer monsoon season were to be average or above average it is likely that soil moisture would be sustained above PWP, facilitating crop growth. The point is that the timing of the summer monsoon is critical for recharging soil moisture reserves which were below PWP for most of June.

Implications of Summer Planting

The conclusion that spring planting was unreliable and therefore unlikely in the Perry Mesa region due to the lack of adequate spring soil moisture reserves has several implications for the agricultural potential of the region. Spring planting is one way to buffer food access by providing multiple attempts to obtain a crop yield. If the spring crop failed or succeeded, farmers could adjust their summer planting schedule. Because spring planting was unlikely or unrealistic, Perry Mesa farmers would have only one period during which to sow a crop. The amount and locations of summer monsoon storms are typically unpredictable, particularly compared to winter moisture, making reliance on summer rain alone very risky.

It is likely that farmers turned to other buffering mechanisms to ensure food availability such as infrastructure improvements to maximize summer rainfall, increased reliance on wild foods, or perhaps intensified food production of semi-domesticates harvestable in other seasons, such as agave and little barley. Limited excavation data from Perry Mesa do not allow for the degree of wild food reliance to be evaluated

(Kruse-Peeples 2013) but may these resources have been viable supplements if summer rainfall for corn production was low.

Several lines of evidence point towards intensified use of agave and little barley in the Perry Mesa region. Rock pile fields, tabular tools, and roasting pits used in the growth and processing of agave are often associated with PMT villages (Spielmann et al. 2011) and the amount of potential harvest could have contributed significantly to the diet in March - May (Kruse-Peeples 2013). Morphological characteristics of little barley recovered from Perry Mesa contexts indicate deliberate human intervention in propagation (Bohrer 1984). Little barley is a cool season grass, growing from winter precipitation and harvested in late spring/early summer. Growth of this food resource would have depended upon a different seasonal precipitation regime and been harvested at a time when stores of other agricultural products would be low. This crop could have extending agricultural production in “more arid regions where early maturity during the cooler part of the year makes maximum use of limited available moisture” (Bohrer 1984:252). Increased investment in agave and little barley was one buffering mechanism likely used by Perry Mesa farmers to minimize the risks associated with farming strategies that relied upon variable summer precipitation.

Linking Soil Moisture Conditions to Agricultural Productivity

In the Hopi region, farmers select maize field locations where soil textures and profile heterogeneity control rates of moisture infiltration, runoff loss, bare soil evaporation, and drainage (Dominquez and Kolm 2005). In the upland region of Perry Mesa, these beneficial characteristics occur within terrace contexts. These benefits are interpreted to be a direct result of terracing and cultivation. It is also possible that these locations had these benefits prior to cultivation which is why they were selected and were further enhanced after they were improved with terracing. Terraces were constructed by concentrating surface stones in locations where subsurface rock density was high which created a semi-pervious surface to subsurface wall that retained moisture by limiting soil water throughflow. Additionally, cultivation practices, such as digging planting holes and tillage, aerated the soil to loosen the characteristically massive structure of the high clay soils on Perry Mesa. This aeration lowered bulk density and improved percolation of soil water to rooting zone depths. Infiltration was further improved through the accumulation of sediments and organic matter trapped behind terraces during surface runoff events.

Several researchers have noted that ideal soil profiles for Southwestern agriculture are characterized by coarse-textures surface layers underlain by fine-grained clayey horizons that hold water in the root zone (see Benson 2011a - cites Bradfield 1971, Hack 1942; Sandor 1995). This study contributes to this finding by demonstrating that the subsurface layers should also have permeable soil structures to increase percolation below the surface zone to spread out into the rooting zones. The coarse-grained texture promotes quick infiltration, limiting evaporation, but the root zone texture must also be loose enough with enough clay texture to promote permeability and retention. The soil layers *underlying* the crop root zones should have the highest clay and most impermeable structure (see also Sandor 1995). It is in these conditions that water will remain in the root zone because it is "blocked" from percolating down into the impenetrable subsurface layer. Soil hydrological conditions are influenced by layering of ideal soil structures and textures (see also Dominquez and Kolm 2005). Soil structure is not permanent. Cultivation practices (tilling, plowing, additions of organic matter, etc.) have the potential to improve conditions by aerating the soil but can also degrade soil structure by compacting the soil. Farmers have the ability to improve soil structure conditions for maximum hydrologic conditions. These improvements have continued to enhance soil water content in terraced locations centuries after abandonment on Perry Mesa.

Chapter 6:

SURFACE RUNOFF AND THE PERRY MESA AGROECOSYSTEM

In order to understand the degree to which surface runoff contributes nutrients to the prehistoric agricultural systems on Perry Mesa, a field collection study was designed that directly captured runoff from terraced and non-terraced areas within the Bull Tank Agricultural Field. This chapter presents the design of the runoff collection study and the results. Specifically three questions are addressed: 1) what are the rainfall conditions that create runoff flow within the upland Perry Mesa landscape, 2) what is the runoff discharge volume and quantity of sediments transported occurring during different seasons and rainfall amounts, and 3) what is the nutrient composition and quantity transported by runoff? The goals of this chapter are twofold. First, these data and results serve as a characterization of a runoff agroecosystem in an upland terrace agricultural setting. Second they present values that will be used for parameters in a simulation model of long-term maize growth presented in Chapter 7.

Environmental Conditions of Surface Runoff

Surface runoff, the rainfall that is not absorbed by the soil and thus flows to a lower elevation, is a major factor responsible for the redistribution of nutrients in semi-arid and arid environments (Ludwig 1987; Turnbull et al. 2011). Runoff also provides additional water that can be harvested to increase moisture availability, ultimately increasing local productivity. Prehistoric and historic farmers in arid and semi-arid environments maximized the moisture and nutrient potential of runoff in a variety of landscape and cultural settings (Barrow 1999; Doolittle 2000).

Runoff is highly dependent upon the surface characteristics of the watershed from which it is derived. Microtopography or surface roughness, slope, vegetation cover, infiltration capacity of the soil, and integrity of soil crusts are just some of the factors that influence runoff dynamics (Parsons et al. 2006; Poesen and Lavee 1994; Schlesinger et al. 1999; Turnbull et al. 2010). Human behaviors such as clearing of rocks and vegetation, construction of terraces, and manipulation of soil characteristics are some of the ways people can influence runoff dynamics.

In addition, differences in the duration and intensity of rainfall can create different types of runoff events (Farquharson et al. 1992; Schick 1988). Winter and summer rainfall in central Arizona is characterized by different intensity and duration dynamics. Winter precipitation, typically December through March, is the result of spatially extensive frontal systems from the Pacific Ocean that are of low intensity and can persist for several hours (Sheppard et al. 2002). Summer precipitation, typically July through September, is part of the North American Monsoon resulting in highly localized convective thunderstorm events of great intensity (Goodrich et al. 1995; 2008; Hastings et al. 2005) that have potential for significant runoff (Fleming 2005). Since both seasons have the potential to influence moisture and nutrient fluxes within field systems, both winter and summer rainfall were targeted during field data collection.

Methods and Procedures

Runoff collection units were installed within the Bull Tank Agricultural field using construction methods established by similar small-scale runoff collection studies (Barger et al. 2006; Lavee et al. 1997; Norton et al. 2007a; Parsons et al. 2006; Schlesinger et al. 2000; Turnbull 2009; Williams and Buckhouse 1991). Four sets of

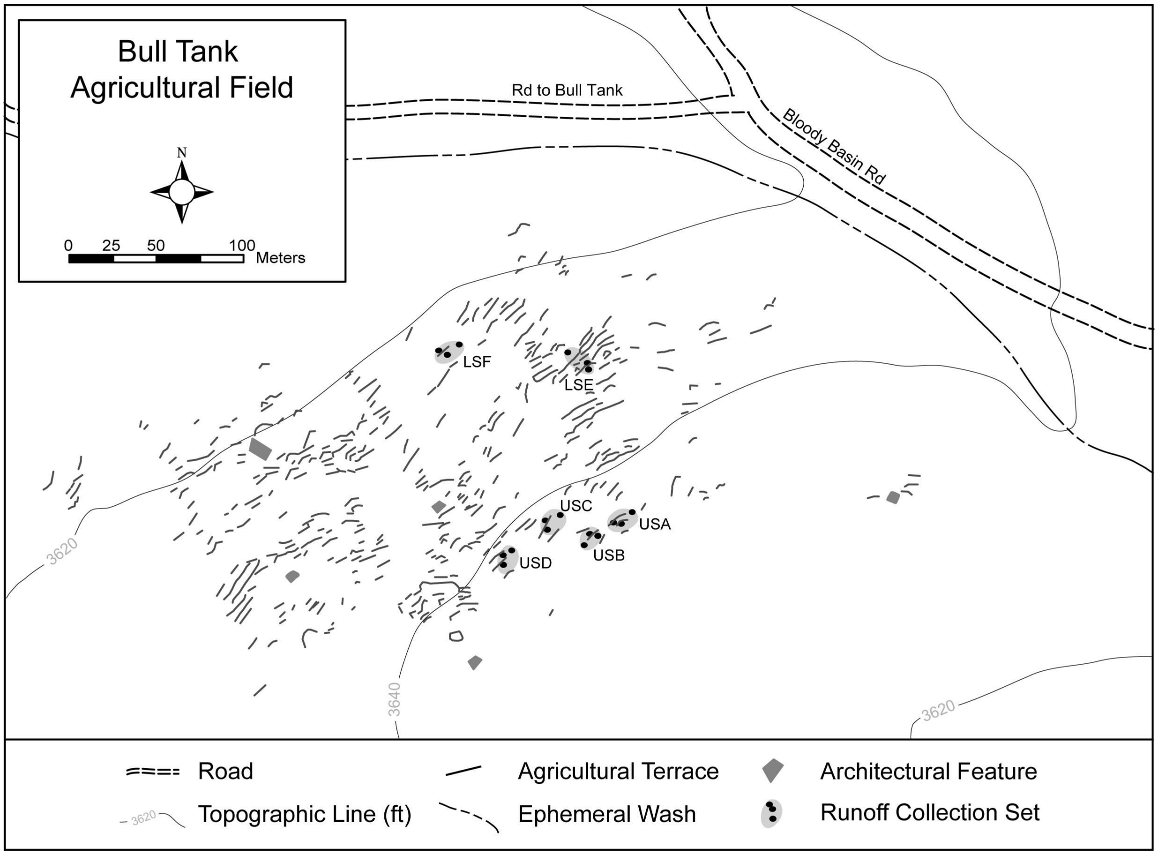


Figure 6.1. Location of runoff collection units within the Bull Tank Agricultural Field.

collections were installed at the top of the hillslope, and two sets were installed at the bottom of the slope of the system (Figure 6.1). More collections were placed at the top of the hillslope to characterize the runoff that would be entering the field system.

Each runoff collection set consisted of three units installed 1) above a constructed terrace (TT), 2) immediately below a constructed terrace (TB), 3) and in an adjacent non-terraced area (NT). Terrace runoff collection units were placed downslope from at least one terrace so the upslope sets are located within the 2nd and 3rd terraces in a series. The downslope terrace-top runoff units were located below several terraces. Terrace top units were installed within the center of a terrace planting surface. All terrace bottom units were installed 10-20 cm downslope from a terrace feature. All of the non-terraced units were in locations with relatively more vegetation and more rock density than the terrace units. Non-terrace units were placed at least 10 or 20 meters away from terraces. They were placed so that the slope length above them represented a similar ground cover to the terrace units.

The collection units were comprised of a triangular metal flashing piece, or a flume, installed flush with the surface on the downslope side of the unit (Figure 6.2, 6.3). The flume had a 0.25 m opening and angled to direct runoff into a 4-liter bucket buried into the ground. The flume and bucket were covered so no direct rain was collected and rain splashes that could transport sediment into the flume or bucket were minimized. The flume was secured in place using nails and was frequently monitored to ensure it would function properly. The 4 liter bucket size was adequate for most observed runoff events, although some overflow did occur and was noted at the time of runoff monitoring. The size and sampling design of the collection units were the result of experimenting and developing a design best suited for this location that would minimize ground disturbance to the archaeological site while also recovering adequate data.

Rainfall data were collected with a digital tipping bucket rain gauge installed in the southwestern portion of the Bull Tank Agricultural Field (Campbell Scientific Inc., precision 0.2 mm). Rainfall totals were recorded at 1 minute intervals during the summer monsoons and 10 minute intervals during the winter because of less frequent field visits for data downloading. This allowed for calculation of rainfall intensity for each storm on a standardized scale (mm/hr^{-1}) and determination of the duration and depth (mm) of individual rainfall events.

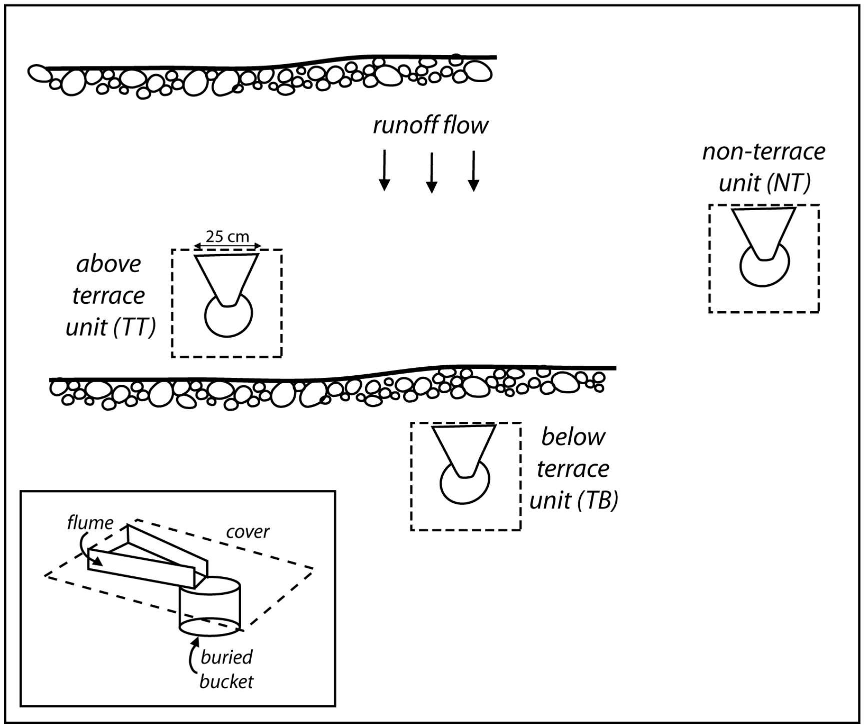


Figure 6.2. Design of runoff collection units.

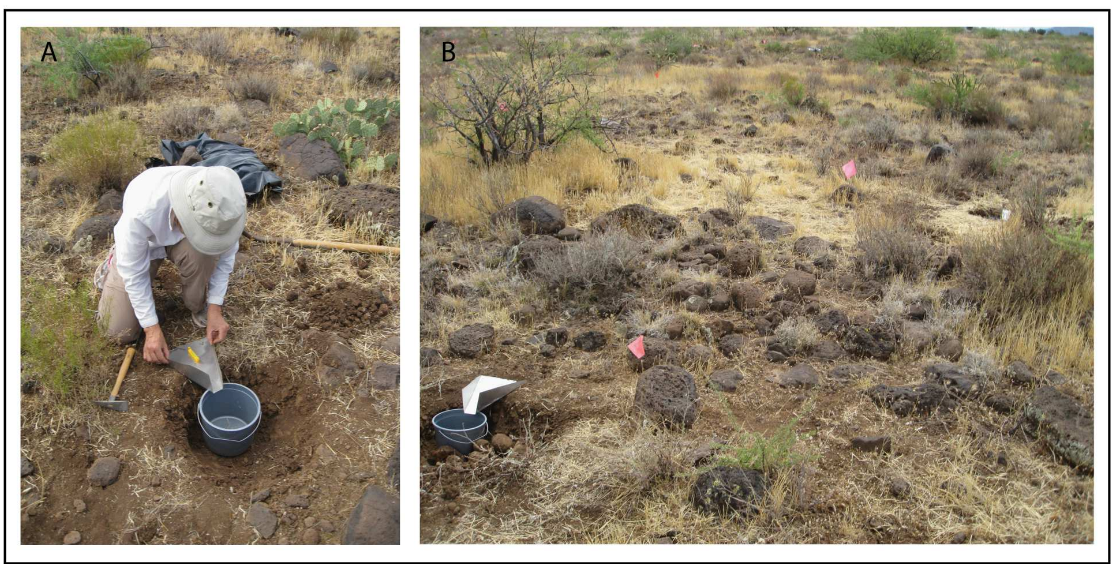


Figure 6.3. Photograph of runoff collection unit installation (A) and runoff unit USA TB (B). Unit covers not present. Photographs taken before the summer monsoon in 2009.

The units were inspected after each rainfall event, typically the morning after. If runoff was present, all of the water and sediment were transferred into acid-washed polypropylene bottles and labeled with the time, date, and unit identification. Samples were stored in a cooler with ice for transport to the lab for processing. If there was less than 50 ml present, the presence of runoff was noted but not collected. Notes were taken about the integrity of the runoff collection sample at the time of collection. Occasionally, a collection bucket had tipped, the flume had become displaced, the cover of a unit had blown off, or rodents were floating in the bucket compromising the integrity of the sample. In these incidences samples may have been processed but results were not always included in statistical analyses, with sample exclusions noted below. Once at the lab, all samples were transferred into refrigeration (4° C).

In this study, runoff collection units were unbounded. They collected runoff from the catchment particular to each location. Based on what other studies have demonstrated (summarized in Parsons et al. 2006), most of the sediment transported via runoff flow is likely from within 7 meters of the upslope area. Sediment transported during runoff events therefore is likely coming from within the terraced field system, particularly for the downslope collection plots, gradually moving farther downslope with each event.

Unit Characteristics

The density and type of vegetation and rock cover have impacts on runoff dynamics (Gyssels et al. 2005; Parsons et al. 2006; Poesen and Lavee 1994; Schlesinger et al. 1999; Turnbull et al. 2011). Therefore, the runoff collection units were located to minimize the variability of vegetation and rock cover between units of the same type so that runoff collections reflected differences in slope position (upper versus lower) and presence of agricultural feature (terrace versus non-terrace) rather than differences in cover.

The percent of cover classes, including different sized stones, vegetation, and bare ground, was recorded for 3 non-overlapping 1x1 m squares in the vicinity of each runoff collection unit (Figure 6.4; n=54) in February just before the peak spring growth. While the ratio of bare ground to vegetation does fluctuate throughout the year as vegetation grows, the same relative vegetation patterns between terraces and non-terraces were observed throughout the year. Stone size classes included gravel (< 7.6 cm), cobbles (7.6 -25 cm), stone (25-60 cm) and boulders (>60cm).

Overall ground cover types are patchy across the field system. However, there are distinct patterns of cover on terrace and non-terrace surfaces. Terrace planting surfaces are relatively cleared of rocks and cover is dominated by vegetation and bare ground whereas non-terrace surfaces are dominated by stones with vegetation also covering significant portions of the surface (Figure 6.4, 6.5). Rock cover of the terrace alignments themselves is generally around 68%, predominately stone- and cobble-sized rocks, with the remaining terrace surface covered by vegetation or bare.

The types of vegetation present are similar across all runoff collection units with grasses occurring more frequently on non-terrace surfaces compared to terrace surfaces. Dominant vegetation is a mix of grasses including tobosa (*Hilaria mutica*), little barley (*Hordeum pusillum*), wild oats (*Avena fatua*), woody vegetation including cat claw acacia (*Acacia greggii)*, prickly pear cacti (Opuntia), and miscellaneous herbaceous species including woolly plantain (*Plantago patagonica*) and Red-stem stork's bill (*Erodium*

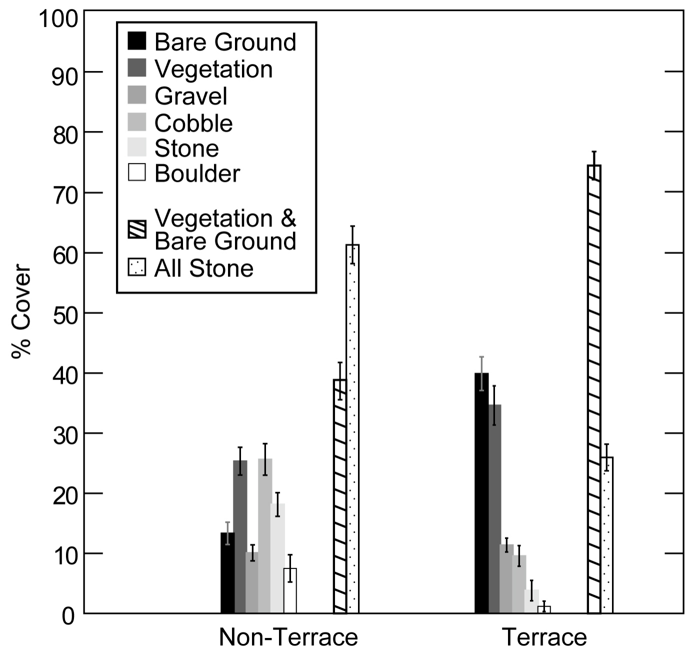


Figure 6.4. Percent cover type for non-terrace and terrace surfaces recorded during winter 2010. Bars indicate the means of all plots of that type and the error bars indicated one standard error from the mean.

cicutarium). Locations immediately below cat claw acacia plants were avoided because these are nitrogen fixing plants and nutrient composition of runoff would be influenced.

Because the terrace system was not maintained after abandonment of the farming system in the 1400s, some terraces have “blow outs.” The entire system is thus not functioning as efficiently as it presumably did during the past. The terrace runoff collection unit locations were selected because they contained more intact features. The collection units were designed to capture all surface overland flow and are likely more efficient than terraces, which would likely only slow and retain a portion of runoff as it continues to flow downslope. The data represent the upper limit of runoff and nutrient inputs for this field location.

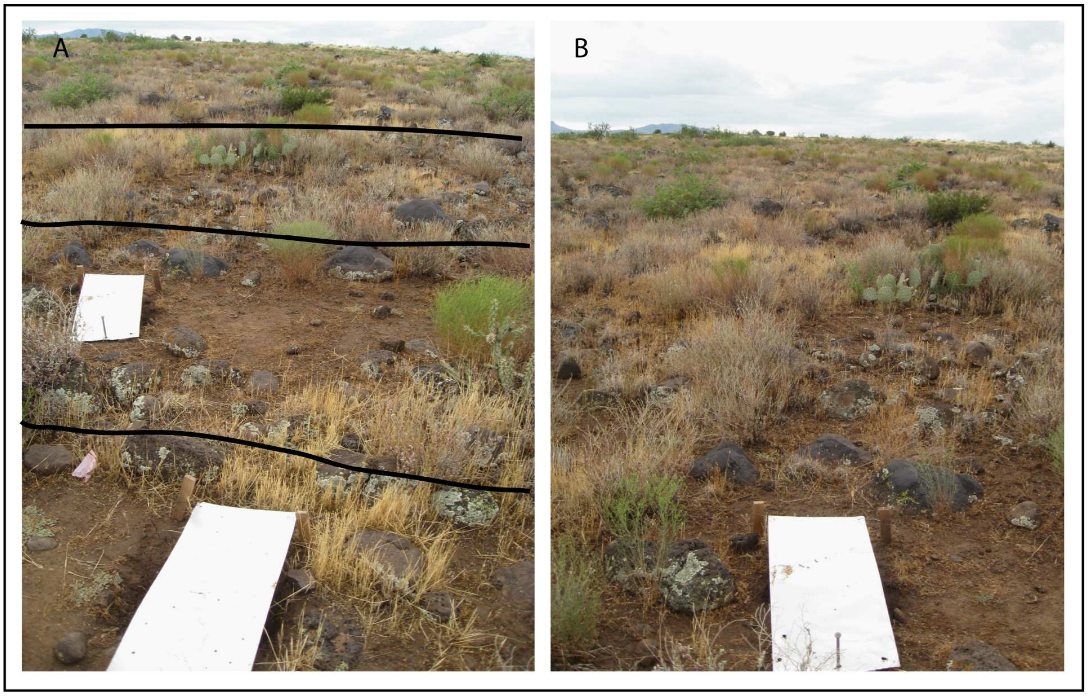


Figure 6.5. Photographs of runoff collection units LSE TT and TB (A) and LSE NT (B). Black lines represent terrace features. Photographs taken after first summer monsoon rain in July 2010.

Laboratory Analyses

The total runoff discharge (ml), total sediment load (g), and suspended sediment concentration (g/L) were measured for each runoff collection sample. Sediment measurements included total carbon (TC) and nitrogen (TN), organic matter (%), and particle size distribution (Table 6.1).

Samples were collected as soon as possible after each rainfall event, put in refrigeration and transported directly to ASU for immediate processing. Rainfall generally occurred in the evening and overnight hours. Field visits and sample collections were made in the early morning. To maintain sample integrity, every sample was treated and stored according to the same protocol. During the winter 2010 collection period, it was difficult to get to the study site for several days after heavy rainfall because of high water in the Agua Fria River. In these instances, the time between runoff and collection was noted and some of these samples were excluded from statistical tests.

Total runoff discharge volume was estimated during field collection and measured in the laboratory as subsamples were processed. In the lab, sample bottles were thoroughly agitated to mix the sample before a subsample was removed. Suspended sediment concentration was determined by the weight of sediment collected from a well-mixed 40 ml subsample that was oven dried for 24 hours. After subsampling, sample bottles were allowed to settle in 4˚C refrigerators for 24 hours and then decanted. Volumes of decanted supernatants were recorded and used to rinse settled sediment from bottles. Sediment was transferred to aluminum tins and dried in a 105˚C oven for at least 24 hours, weighed, and subsampled for sediment analyses or stored in sealed plastic bags for future analyses. Remaining supernatant was discarded. The weight of the total amount of sediment was determined by combining the recorded weights of all sediment in the subsamples and the total amount of sediment weight after samples were decanted.

All analyses of the sediments were completed on single samples if there was enough sediment available, ca. 60 g. If a single collection unit did not produce enough sediment for all the proposed physical and chemical analyses, collections were aggregated based on runoff event, season, and sample location type (i.e., aggregated upslope terrace-tops or aggregated downslope non-terrace units). Because sediments were settling in collection bottles for at least 24 hours and samples were generally small, Inorganic N concentrations were not measured. Soils from Perry Mesa have very low to no carbonates (Trujillo 2011) and therefore the total carbon content is assumed to be very similar to or the same as organic carbon levels.

Nutrients may be transported in runoff either in solution (dissolved forms) or attached to the sediment (particulate forms) transported by the flow (Walton et al. 2000). Dissolved forms come from the rainfall itself and from the soil as water travels across the ground surface. Nutrient transport in dissolved forms has been shown to be low in semi-arid environments (Schlesinger et al. 1999, 2000). Particulate-bound forms are thus the primary nutrients transported by runoff, particularly particulate-bound nitrogen, carbon, and phosphorus (Barger et al. 2006; Turnbull 2009, Turnbull et al. 2011). For example, Barger and colleagues (2006:260) observed that 98% of the total carbon and nitrogen contained within runoff was associated with sediments and the remaining 2% associated with dissolved forms. Some of the particulate-bound nutrients of transported sediments are immediately available for plant uptake as liable, plant accessible, NO3-N and NH4-N forms (Lister 2007). The extent to which a receiving landscape patch is supplied with NO3-N and NH4-N from runoff depends on the distance runoff has traveled (flowpath length) which influences nitrification rates, as well as the length of the antecedent dry period (Welter et al. 2005). Most of the nitrogen that is transported by runoff is non-liable in form, however, and will become available over the long-term as mineralization processes occur. Therefore, analyses of the chemical nutrient properties of runoff presented in this study focused on the sediments transported by runoff, particularly the total nitrogen concentrations, rather than the dissolved and liable forms.

Although this study focuses on runoff gathered hundreds of years after the terraces were used, it is assumed that nutrient pools in the runoff are similar to the past, based on the presence of similar vegetation communities between today and the past Briggs et al. 2007) and similarities in soil characteristics between terraces and non-terraced locations (Chapter 4).

Table 6.1. Summary sediment datasets.

Dataset	Method
Total Carbon and Nitrogen (g/kg-1)	Dry combustion/gas chromatography using a Costech ECS 4010 CHNSO Analyzer (Costech Analytical Technologies, Inc., Valencia, California, USA) at ASU, Tempe, AZ. Subsamples were pre-ground using a steal ball mill to pass a 76 µm sieve (Sparks 1996).
C/N Ratio	Determined with the results of the TN and TC analysis.
Organic Matter (%)	Loss-on-ignition (LOI). Ash-free dry mass recorded after combustion of oven-dried soils for 4 hours at 550°C.
Particle Size (<2mm, %)	Hydrometer method (Gee and Or 2002). Samples pretreated with sodium hexametaphosphate solution for clay dispersion. Hydrometer readings followed by sieving to 53 µm for sand fraction and determination of silt fraction by difference. Particle-size distribution is classified as gravels (> 2 mm), Sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (less than 0.002 mm). Results discussed in Appendix C.

Collection Periods

Runoff collection units were established in August 2009 and monitored until mid-October, 2010. As discussed in Appendix C, the 2009 monsoon yielded no runoff in this period and thus the summer monsoon data for this study are only from 2010, June 29 – October 15. The winter monitoring period occurred from January 1 – March 30, 2010. Details of the observed rainfall and runoff events are presented in Appendix C.

Results

The results of the runoff collection study that relate to the simulation model developed in Chapter 7 are presented below. Additional results of the runoff collection study are discussed in Appendix C. The first results section determines what types of rainfall depths, or amounts, are necessary to produce runoff during the summer and winter. The relationships among the amount of runoff discharge, the volume and sediments moved, to rainfall depths and intensities are also explored. Results indicate that rainfall depth, or amount, is a reasonable predictor of runoff discharge. This is significant because simulation of long-term runoff dynamics must make use of historic rainfall data which are only available as daily depths, not intensity or rainfall duration. The second results section discusses the nutrient characteristics of runoff discharge including the concentration of nitrogen. Additional comparisons of runoff discharge from different collection contexts, the nutrient conditions of runoff, and the comparison of runoff to matrix soils are presented in Appendix C.

Rainfall Depth and Runoff

The total amount of rainfall per discrete event which produced runoff ranged from 12 to 44 mm (0.47 to 1.7 in) during the winter and 3.8 to 35.4 mm (0.14 to 1.39 in) during the summer, however substantial runoff was only produced with at least a 7 mm (0.28 in) event in summer. Based on the observed period it is inferred that it would take a storm amount greater than 7 mm to produce a measurable runoff event in the summer and an event of at least 11 mm, and probably more than 20 mm if antecedent conditions are dry, during the winter. Differences between summer and winter are due to the different storm dynamics during these seasons. The lengths of winter rainfall events are considerably longer compared with the summer events, which typically occurred as short-lived intense thunderstorms. In general, summer monsoon storms are characterized by high intensity but low overall depth (precipitation amount) whereas high intensity storms are rare during winter but depth tends to be greater. Because of the different intensity and depth dynamics, winter and summer events are discussed separately.

A total of 47 measurable rainfall events and 12 runoff events were observed during collection periods (Table 6.2). A rainfall “event” is considered to be a discrete storm that is preceded and followed by a dry period longer than the time length of the event. A runoff event is a rainfall event that produced runoff in at least 1 collection unit. If runoff did occur, it typically was present in several collection units. However a few smaller rainfall events produced runoff in only 1 or 2 units.

Table 6.2. Summary of runoff collection periods and runoff events.

Collection Period	**Total Amount of Rainfall Recorded mm/inches**	**# of Rainfall Events (>0.2 mm)**	**# of Runoff Events**	**# of Processe d Runoff Samples**
Summer 2009	10.8/ 0.43	6	0	**0**
Winter 2010	289.2/ 11.38	17	5*	**28**
Summer 2010	117.6/ 4.62	24	7	**54**
TOTAL	**417.6/ 16.44**	**47**	**12**	**82**

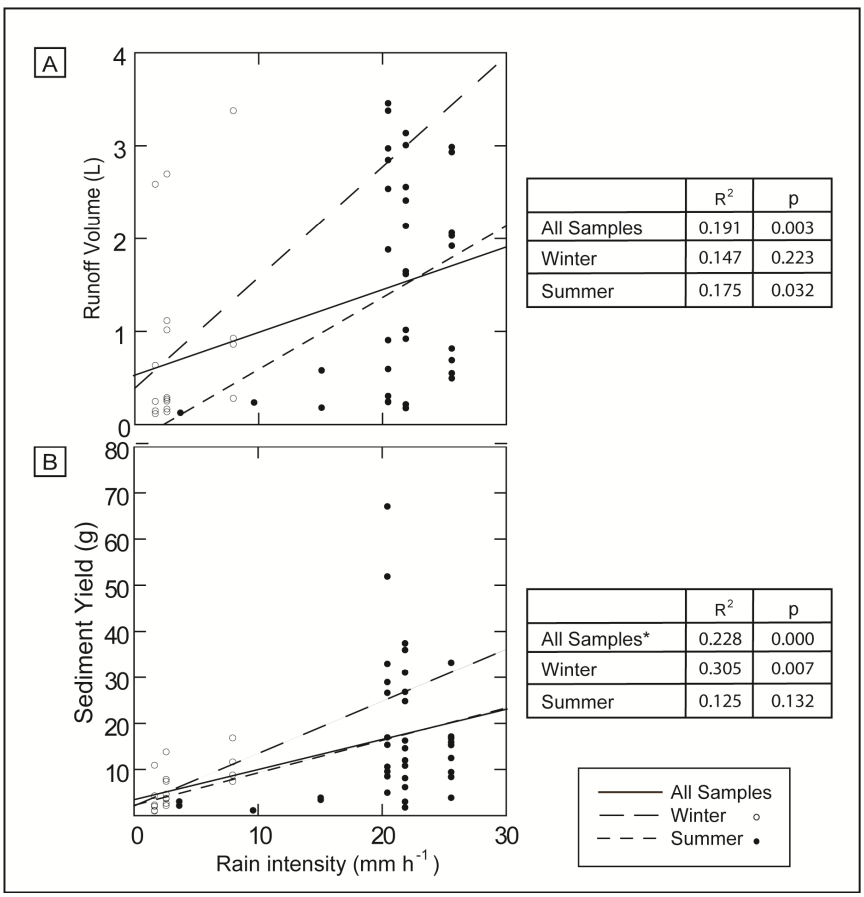
*High streamflow in the Agua Fria River prevented access after individual rainfall events. It is likely that more discrete events generated runoff than listed. This number presents the total amount of observed runoff events.

A total of 82 viable runoff samples were collected and processed from the three collection periods (Table 6.2, Appendix D.1). This number does not include runoff events that produced <50 ml in the collection. Nor does it include samples where runoff was clearly produced but was not collected because of contamination or collection spillage (i.e., dead rodent present or collection bucket was washed away).

Influence of Rainfall Depth and Intensity on Runoff Discharge. Higher intensity and precipitation amounts (depth) of individual rainfall events resulted in higher runoff discharge volume and greater sediment yields (Figure 6.6, 6.7). This indicates that both rainfall intensity and depth are reasonable predictors of runoff volume and sediment yields. Storms with the most potential to transport large amounts of sediment, and therefore nutrients, are intense, prolonged summer storms.

The strength of the relationships between runoff volumes, sediment yield and sediment concentration, and the rainfall dynamics of intensity and depth was determined using Pearson's correlations. Each relationship is graphed as a scatter plot with a smoothed linear line to show relationships. The r^2 and p-values are reported and significance levels were defined at the 0.05, 0.01, and <0.001 levels. Coefficients of variation (C.V.) were also determined for winter and summer events. These analyses do not include runoff collections from more than 1 single rainfall event since the runoff volumes and sediment yields are mixed. In addition, these analyses do not include individual collections that likely overflowed collection buckets nor do they include data from collections with no runoff or <50 ml, which were noted but not collected.

The correlations between rainfall intensity and runoff discharge volume and sediment yields are statistically significant when considering all samples ($p=0.05$; Figure 6.6: A, B). The more intense the rainfall event, the more runoff discharge volume and the more sediment is transported. The correlation between rainfall intensity and runoff volume is also statistically significant for summer events alone (*p=0.03*) but not for winter events (*p=0.223*). Winter and summer events have different rainfall intensity dynamics and the amount of runoff moving in winter storms is related more to the duration of the event, not the intensity. The intensity of rainfall, however, is correlated with the amount of sediment transported in the winter (*p=0.007*) indicating that high intensity storms do have the ability to transport larger amounts of sediment in the winter even though the relative intensities are lower than in summer.



	R^2	p
All Samples	0.191	0.003
Winter	0.147	0.223
Summer	0.175	0.032

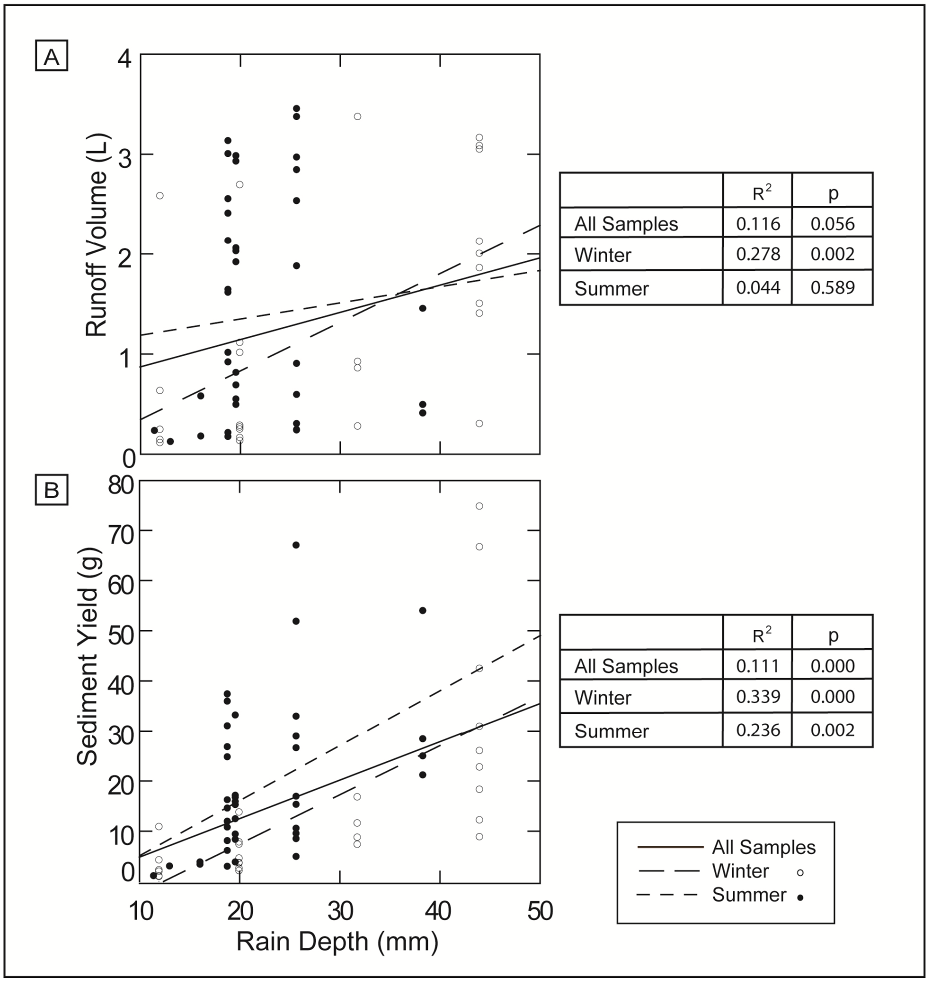
	R^2	p
All Samples*	0.228	0.000
Winter	0.305	0.007
Summer	0.125	0.132

Figure 6.6. Runoff volume (A), sediment yield (B) as a function of rainfall intensity.

The correlation between runoff volume and rainfall depth, or amount, is not significant when both winter and summer are considered collectively (*p=0.*056) but is significant when only winter samples are considered (*p=0.002;* Figure 6.7: A). This indicates that the greater amount of rainfall during the winter, the greater the runoff volume. But, considering the intensity information presented above, the greater intensity of a storm the greater amount of runoff volume during summer storms. There were relatively few observed summer storms that were over 30 mm, however, and if more were to have occurred it is likely that runoff volume would also be significantly correlated with rainfall depth during the summer.

The correlation between sediment yield and rainfall depth is significant for all samples (*p=<0.001;* Figure 6.7:B). This indicates that the greater amount of rain the more sediment is transported. Therefore, it can be concluded that the greater quantity of rainfall the more runoff and sediment will be transported and that rainfall depth is a reasonable predictor for the quantity of runoff sediments transported. However, it should be noted that there is a great deal of variability in the samples associated with high intensity and high yielding rainfall events, indicating that not all large events lead to large runoff outputs in all locations.

While the relationships between rainfall intensity and depth (amount) to runoff volume and sediment yields may be statistically significant, as noted above, the values can also be highly variable. The variability is highest for low intensity winter runoff events (C.V.= 0.93) compared to higher intensity summer events (C.V.=0.69). In addition, many low intensity winter runoff events did not transport a substantial amount of sediment ($\bar{x}$=15.26) compared to higher intensity summer events ($\bar{x}$ =33.07). However,



	R^2	p
All Samples	0.116	0.056
Winter	0.278	0.002
Summer	0.044	0.589

	R^2	p
All Samples	0.111	0.000
Winter	0.339	0.000
Summer	0.236	0.002

Figure 6.7. Runoff volume (A), sediment yield (B) as a function of rainfall depth.

sediment yields from both winter and summer events were extremely variable (C.V.=1.24 and 1.23 respectively). A few low intensity storms that occurred during the winter resulted in high runoff volumes. This is likely because these intensities, although low, were prolonged storms, resulting in high runoff volume but low overall sediment yield. The high degree of variability of observed runoff discharge may be the result of small-scale rainfall dynamics that were not monitored at the scale of this study. Small scale spatial variability of rainfall depth and intensity, even over a few hundred meters, can translate into a high degree of variability in runoff dynamics which influence the overall runoff volume discharge and sediment yield (Faures et al. 1995; Goodrich et al. 1995; Hastings et al. 2005).

Runoff Discharge and Collection Context. Some of the variability in runoff and sediment yield can be explained by examining not only intensity and depth, or amount, of rainfall events but the landscape contexts of sample units that yielded runoff. Generally, results indicate that more runoff and sediment move within terrace contexts compared to non-terraced contexts but the results are equivocal (Appendix C).

Nutrient Characteristics of Runoff Discharge

Analyses of runoff nutrients focused on the concentrations of nitrogen, carbon, and organic matter found in the sediments (Table 6.3; Appendix D.1). Nutrient concentrations were converted to nutrient pools to determine the nutrient content of an entire runoff sample. These values were used in the simulation model discussed in Chapter 7 (see Figure 7.2). All analyses subdivided the dataset into winter and summer samples. Nutrients, particularly nitrogen, continually cycle as plants grow, die, and decay and it was expected that the seasonality of samples would influence the nutrient content of runoff sediments.

One-way ANOVA analyses with post hoc Tukey tests were performed for each runoff collection context to identify differences in nutrient concentration between the summer and winter seasons (Table 6.3) and terrace and non-terrace contexts (Appendix C). Significance levels were defined at the 0.05, 0.01, and <0.001 levels. There are no significant differences between winter and summer runoff events in terms of the total nitrogen, total carbon concentrations, and the carbon to nitrogen ratio (Table 6.3). Data values used in the simulation model, however, still distinguish winter and summer rainfall events because the amount of runoff sediment yield is dependent upon rainfall depth and intensity, which vary by season. Therefore, the overall nutrient pools vary, with summer producing greater nutrient pools transported in runoff.

There is a no significant difference in the amount of organic matter between summer and winter runoff events (*p=0.054,* Appendix D.2) based on the predefined significance levels. However, there is a slightly higher concentration during summer events. Summer periods represent the time of year when there is the most abundant dead biomass on the landscape and the slightly elevated organic matter content of runoff sediments from this period likely reflects this pattern.

Table 6.3. Comparison Winter (n=28) and Summer (n=51) runoff nutrients.

		Mean	S.D.	P-value
Total Nitrogen (g/kg^{-1})	W	1.992	0.728	0.866
	S	1.961	0.799	
Total Carbon (g/kg^{-1})	W	22.961	8.996	0.704
	S	22.126	9.443	
C/N	W	11.442	1.041	0.982
	S	11.285	0.922	
Organic Matter %[a]	W	5.805	0.933	0.054*
	S	6.727	1.922	

[a]Winter (n=12) and Summer (n=26).
*Significant at 0.05.

It is important to note that the nutrient concentrations in runoff are higher than the parent soil matrix within the Bull Tank Agricultural Field (see Appendix C). In general, runoff sediments are more nutrient-enriched compared to matrix soils due to the tendency of organic matter to be located near the surface and the affinity of soil nutrients to be bound to fine sediment particles, which are proportionally transported by runoff (Jin et al. 2009; Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Ramos et al. 2006; Sharpley 1985, Turnbull et al. 2011). The runoff potential and nutrient quality of transported sediments would be harnessed with the construction of terraces. This is how farmers would maximize the renewal effect of runoff for fertility.

Runoff Nutrients and Rainfall Dynamics. No clear relationships were observed between total nitrogen concentration and rainfall intensity and depth (Appendix C). There are significant relationships between rainfall dynamics and the composition of nutrients, however, measured by the carbon to nitrogen ratio (C/N; Appendix C). This ratio is a proxy for the level of organic matter decomposition. The more decomposed, the higher proportion of nutrients will be bioavailable for plant uptake. The earliest storms in the summer produced the highest quality, or more decomposed organic matter, compared to later season storms. Additionally, the quality of organic matter decreased the greater the rainfall depth and the more intense the storm. Due to the complexity of these relationships the simulation model considers the total nitrogen concentration. Farmers would realize that the first intense storm of a season would have the ability to “flush” the landscape of decomposing organic matter and that this debris would be of high quality.

Chapter 7:

SIMULATION MODEL OF LONG-TERM MAIZE GROWTH

Understanding prehistoric agricultural productivity requires an appreciation of numerous factors including climate, fertility, and cropping choices. Traditionally, models of productivity in the American Southwest have placed a preference on climate dynamics, particularly precipitation, and natural soil moisture retention (e.g., Van West 1994; Van West and Altschul 1994, 1997). While this approach allows for investigation of conditions over long time scales and considers important factors for agriculture in arid regions, it underplays the role of soil fertility in long-term agricultural sustainability. In addition, the role humans have in improving fertility, as well as moisture, needs to be incorporated into our understanding of agricultural production.

In this chapter I discuss a long-term simulation model that couples maize plant growth, soil nutrient dynamics, surface runoff, climate, and the recursive interactions among these variables, to understand how they interact to determine variations in soil fertility through time. The simulation focuses specifically on soil nitrogen, considered here as a long-term proxy for soil fertility, an important factor in agricultural productive potential. This type of modeling approach does not simulate specific food yields (such as bushels of corn per ha) but rather focuses on the conditions that influence crop productivity. The accuracy of available climatic, environmental and yield data of ancient cultivars is not appropriate for exact annual calculations of yield. Instead, this model is used to examine the conditions that influence long-term soil fertility and shifts in agricultural capacity over time. The model is parameterized using data from Perry Mesa discussed in previous chapters of this dissertation. This approach allows for a quantitative assessment of how soil fertility might change through time under a maize cropping system that integrates surface runoff in nutrient renewal.

I conclude, from a fertility standpoint, that farming on Perry Mesa would have been difficult and integration of runoff as a nutrient source would have been essential. Management of runoff leads to slower rates of nutrient decline compared to when runoff is not managed to replenish the soil. Even when runoff is considered as a nutrient replenishment source, however, letting fields lay fallow is still necessary to allow nutrient levels to recover. This would have implications for the amount of land necessary for agriculture on the Perry Mesa landscape as well as demands upon agricultural labor. A portion of arable land would need to be uncultivated but runoff still actively managed to support long-term production on this landscape. Climate is also very important. Not only does rainfall allow crops to grow, but rainfall frequency and amounts determine the frequency and amount of runoff in this landscape and therefore the amount of nitrogen transported by runoff. Soil nutrient declines are slower during wet climate regimes and faster during dry regimes. Fallow times are therefore shortest during wet regimes and longest during dry regimes. Chapter 8 integrates a landscape model of agricultural land and population density to evaluate whether there was enough arable land available for the populations living on Perry Mesa to undertake the fertility maintenance strategies of runoff management and fallow cycling suggested by the simulation model.

The Simulation Model of Long-term Soil Fertility

The following discusses the variables used in the simulation model, their data sources, and the specific values used (Table 7.1, 7.2). The model used in this analysis was developed for the types of data available for the Perry Mesa agroecosystem but is flexible enough to be applied to other regions. It is similar to models of ecosystem dynamics, such as CENTURY (Parton et al. 1987), but requires fewer variables and allows for the integration of nutrients transported by surface runoff. The model focuses on nitrogen fluctuations as an index of soil fertility. As considered here, nitrogen sources include the soil and sediments transported in surface runoff.

Table 7.1. Simulation model variable definitions.

I_t	Inorganic nitrogen at time *t*
N_t	Total nitrogen pool of the soil profile of a planting hill at time *t*
β_s	The annual mineralization rate of the soil
β_r	The annual mineralization rate of runoff sediments
$\alpha_{a,, b, c}$	The proportion of inorganic nitrogen retained or carried over to the next time step denoted as subscripts *a, b, c*.
$r_{a,, b, c}$	Total nitrogen pool of runoff dependent on intensity of rainfall events denoted as subscripts *a, b, c*.
x	The number of each type of runoff event within a year based on the precipitation regime simulated.
E_t	The amount inorganic N that remains after maize needs are met at time *t*
M	The nitrogen needs of maize.

Variable values were derived from the interquartile range of the soil and runoff data collected in the field and discussed in Chapters 4 and 6. The values represent a low, median, and high estimate for each variable. All variables discussed in this chapter use these designations. The 1st quartile value, denoted as low, is the value where only 25% of the range of values falls below this number. The 2nd quartile value, denoted as the median, represents the median value of the range. The 3rd quartile value, denoted as high, is the value where only 25% of the range of values falls above this number.

Table 7.2. Data origins and states of variables used in the model.

<table>
<tr><th>Model Variable</th><th>Values</th><th colspan="4">Variable States</th><th>Data Origin</th></tr>
<tr><td rowspan="3">N_t</td><td rowspan="3">Table 7.3</td><td colspan="4">Low</td><td rowspan="3">Total nitrogen data from excavated trenches in Bull Tank Agricultural Field (Ch. 4).</td></tr>
<tr><td colspan="4">Median</td></tr>
<tr><td colspan="4">High</td></tr>
<tr><td>β_s</td><td>Table 7.4</td><td>0.5</td><td>1.5</td><td>2.5</td><td>3.5</td><td>Values represent the range of possible annual mineralization rates (after Brady and Weil 2007; Niemeijer 1998).</td></tr>
<tr><td>$\alpha_{a,, b, c}$</td><td></td><td>$\alpha_a = 0\%$</td><td>$\alpha_b = 50\%$</td><td colspan="2">$\alpha_c = 100\%$</td><td>Inorganic nitrogen not assimilated into maize will be carried over into future time steps.</td></tr>
<tr><td>β_r</td><td></td><td colspan="4">1.5</td><td>Assumed rate of mineralization of runoff sediments derived from Lister (2007).</td></tr>
<tr><td rowspan="3">$r_{a,, b, c}$</td><td rowspan="3">Table 7.10, 7.11</td><td rowspan="3">High = r_a</td><td rowspan="3">Moderate = r_b</td><td rowspan="3">Low = r_c</td><td>Low</td><td rowspan="3">Data from runoff collections (Ch. 6) provided the total g of nitrogen in runoff sediments. Data separated by winter and summer the type of rainfall event (*a*, *b c*). It was assumed 30% of the runoff would be retained.</td></tr>
<tr><td>Median</td></tr>
<tr><td>High</td></tr>
<tr><td>x</td><td>Table 7.13</td><td>Wet</td><td>Average</td><td>Dry</td><td>Average frequency</td><td>Average frequencies of the type of rainfall event (*a*, *b c*) that occur during a year based on historic weather station data (WRCC 2009) determined for each climatic regime based on paleoclimatic reconstructions (Ingram 2009).</td></tr>
<tr><td rowspan="3">$r_{a,, b, c}$</td><td rowspan="3">Table 7.10, 7.11</td><td rowspan="3">High = r_a</td><td rowspan="3">Moderate = r_b</td><td rowspan="3">Low = r_c</td><td>Low</td><td rowspan="3">Data from runoff collections (Ch. 6) provided information on the total g of nitrogen transported in runoff sediments. Data separated by the type of rainfall event (*a*, *b c*) occurring in winter and summer. It was assumed 30% of runoff would be retained.</td></tr>
<tr><td>Median</td></tr>
<tr><td>High</td></tr>
<tr><td rowspan="3">M</td><td rowspan="3">Table 7.12</td><td rowspan="3">Present = cropped</td><td colspan="2" rowspan="3">Absent = fallowed, no nutrient uptake</td><td>Low</td><td rowspan="3">Data based on the nitrogen content of traditional maize varieties grown under rainfall and runoff conditions (from Jonathan Sandor, personal communication). Model assumes 4 maize plants occupy a single planting area based on ethnographically documented planting strategies.</td></tr>
<tr><td>Median</td></tr>
<tr><td>High</td></tr>
</table>

Variable Parameters

The Nitrogen Cycle

As many of the variables deal with nitrogen in different forms, it is useful to briefly review the nitrogen cycle here. Nitrogen is an essential nutrient for plant growth that is limited in arid and semi-arid environments (Ludwig 1987). It exists in soils in organic and inorganic forms and continually cycles from one form to another. The total amount of organic and inorganic nitrogen is referred to as the total nitrogen (TN) pool. Organic matter, decomposed plant material and humus, contains approximately 5% nitrogen. In order for this organic nitrogen to be available for plant growth it must be converted into inorganic nitrogen (IN) forms of ammonium (NH_4^+) and nitrate (NO_3^-) through processes called mineralization. It is these forms of nitrogen that are assimilated into plants, supplying plant cells with nutrients, facilitating growth. Mineralization is carried out by microorganisms and influenced by soil moisture, temperature, oxygen, the C:N ratio and the type of organic materials in the residue. Atmospheric nitrogen (N_2) is readily abundant but only limited amounts can be made available to plants through processes of biological nitrogen fixation. Inorganic nitrogen can also be converted to organic nitrogen, forms unavailable to plants. This process occurs when oxygen is limited, such as the case during waterlogged conditions. While biological nitrogen fixation and denitrification are certainly processes that occurred in the Perry Mesa agroecosystem, they are not directly considered in this version of the simulation model.

Because nitrogen must be in inorganic forms to be available to plants, the simulation model focuses on the changing amounts of inorganic nitrogen. The ratio of inorganic N to TN is in constant flux and depends upon the state of plant growth and decay, as well as when moisture and temperatures are adequate for mineralization to occur. For the purposes of the simulation model, I assumed that a certain amount of the nitrogen found in the soil is converted to inorganic nitrogen each year according to an annual mineralization rate. Similarly, a proportion of nitrogen transported in runoff is assumed to be immediately available for plant growth as inorganic nitrogen. The parameters used to determine these proportions are described in detail below.

An agroecosysem deficient in nitrogen ultimately reduces crop yields and quality. Nitrogen is an essential component of amino acids which are the building blocks of all proteins and enzymes (Brady and Weil 2007). For maize, nitrogen deficiencies lead to chlorosis (yellowing of leaves), stunted growth, loss of disease resistance, smaller kernel and ear size, poor kernel set, and less protein content of grain (Bloom 1997; Gardner et al. 1985; Olson and Sander 1988; Uhart and Andrade 1995).

Total Nitrogen (N) and Inorganic Nitrogen (I) Pools in Agricultural Soils

The amount of soil present within the modeled area was determined to be 3,613,070 g based on the average bulk density and thickness of each soil stratum present in collections from the Bull Tank Agricultural Field (Chapter 4). The interquartile range of the amounts (g) of Total N within the soil profile were based on the distribution of Total N concentrations derived from the terrace and non-terrace Bull Tank samples (Table 7.3). The spatial dimensions of the modeled area are based on a 40 cm soil depth of excavations in the Bull Tank Agricultural Field (Chapter 4) and ethnographically documented dryland maize spacing of 2.3 m ((Bradfield 1971; Brown 1952; Cushing 1920; Manolescu 1995).

Recent soil biogeochemistry data from terraced and non-terraced contexts near Pueblo la Plata on Perry Mesa indicate that prehistorically farmed soils (terraced areas) are not currently nitrogen-depleted when compared to soils that were likely not cultivated prehistorically (non-terraced areas [Trujillo 2011]). Therefore, using present soil nitrogen levels is appropriate for model parameters of the pre-agricultural nutrient pools.

Table 7.3. Values for N_1.

	TN (g)
Low	2786.45
Median	2883.12
High	3140.66

The range of TN values in Table 7.3 was used as the starting point to calculate the inorganic N pool after set mineralization rates were applied (Table 7.4). Annual rates of 0.5%, 1.0%, and 1.5% were used to represent the possible range of mineralization (after Brady and Weil 2007; Niemeijer 1998). Therefore the simulation results present the changes in nitrogen pools with a mineralization rate of 0.5% representing a low estimate and 1.5% representing a high estimate. The mineralization rate has a strong influence on the value of *I* (inorganic nitrogen; Table 7.4). Assumptions of a higher rate allow for a much larger proportion of nitrogen available than lower rates.

Table 7.4. Values for I_1.

Mineralization Rate (β_s)	Range of *I*		
	Low	Median	High
0.5%	13.93	14.42	15.70
1.0%	27.86	28.83	31.40
1.5%	41.79	43.25	47.12

Brady and Weil (2007) report that annual mineralization rates of soils are typically between 1.5-3.5%. However, they are drawing largely from soils found in humid environments where most likely nitrogen fertilizer has been applied. Annual mineralization rates for semi-arid soils, like those on Perry Mesa, are likely to be lower than the 1.5-3.5% scale. For example, the proportion of inorganic N within a context in India, semi-arid cultivated vertisols similar to Perry Mesa, was 0.96% for fields with manure applications and 0.97% for fields treated with chemical fertilizers. While the overall total N was higher in treated fields, the proportion of available nitrogen was the same, less than 1% (Wani et al. 2003). Based on information about dryland mineralization rates, a scale of 0.5-1.5% was used. In reality there would be periods during the year when mineralization rates might exceed 1.5%, such as after a rain when soils are moist and microbial activity elevated, and periods when mineralization might be less than 0.5% when temperatures are high and soils are dry. The rate used in the model is considered to be an average rate over the course of the year.

A proportion of the mineralized *I* not assimilated into simulated maize growth is carried over in subsequent time steps (α). Three states are used, 0%, 50%, and 100% denoted as subscripts *a, b, c.* Excess inorganic nitrogen can be lost from the system via leaching, denitrification, or assimilated into weeds or winter vegetation. Using the range of values for α allows for a determination of the range of modeled nutrient fluctuations.

Total Nitrogen (r) and Inorganic Nitrogen ($r\beta_r$) Pools of Runoff Sediments

The model focuses on nitrogen inputs to the agroecosystem from sediments transported by runoff. The measured nitrogen content of runoff described in Chapter 6 provides data for this parameter in the model. It has been demonstrated that the sediments (rather than the solution), the particulate bound forms of nitrogen, account for the highest proportion of nitrogen transported by runoff in semi-arid shrub and grassland environments (Barger et al. 2006; Turnbull et al. 2011). Fine sediments carried during runoff events have a high nitrogen concentration, whereas precipitation has relatively low nitrogen concentrations. Therefore the simulation only considers the nitrogen from sediments transported by runoff.

Long-term precipitation data from the Sunset Point weather station provided information on the range of daily rainfall events that is likely characterizes the Perry Mesa region (Figure 7.1). Six categories of rainfall were determined based on the histograms of daily rainfall totals. Categories include none (0 mm), trace (<1.1 mm), light (1.1-6.99 mm), low intensity (7.0-15.0 mm), moderate intensity (15.1-27.0 mm), and high intensity (>27.1 mm). The runoff collections made in this study serve as the basis for determining the probable TN pools of runoff events that occur during only the low, moderate and high intensity rainfall categories (see Table 7.5).

Runoff dynamics were different during the summer and winter seasons (Chapter 6) and therefore summer and winter data were kept separate for determining the amount of nitrogen deposited per runoff event. While there are no significant differences in the nutrient concentration between winter and summer runoff events (see Table 6.3) there are significant differences when the total nutrient pools are considered. Winter runoff events have considerably lower TN pools than summer events (Figure 7.2). Winter runoff events are simply smaller and transport fewer sediments. Moderate and low rainfall categories transport similar nitrogen pools. The high rainfall category has the highest potential

Table 7.5. Rainfall event types and runoff events.

Rainfall Event Type	Daily precipitation (mm)	Daily precipitation (inch)	Runoff Event Data (# of samples)	
			Summer	**Winter**
High	>27.1	>1.06	10/7/2010 (12)*	1/20/2010 (4) 3/14/2010 (9)
Moderate	15.1-27.0	0.59-1.06	8/18/10 (13)	3/2/2010 (9)
Low	7.0-15.0	0.28-0.59	7/25/2010 (2) 7/30/2010 (11) 9/22/2010 (13)	2/9/2010 (6)
Light	1.1-6.99	0.04-0.28	NA	NA
Trace	<1.1	<0.04	NA	NA
None	0	0	NA	NA

* Storm occurred after the traditional summer monsoon season but is considered part of the summer 2010 monsoon (CLIMAS 2010b).

nitrogen deposition for both the summer and winter. It is the high rainfall events, particularly in summer, that have the greatest nutrient renewal potential.

The quartile ranges of the TN pools of the representative runoff events of each rainfall category were calculated (Table 7.6). It was assumed that 30% of the runoff would be retained within terraces and subsequently 30% of the TN pool of runoff retained (Table 7.7). The 30% rate was assumed to be a realistic estimate of agricultural terrace runoff retention efficiency. This rate assumes that 70% of sediments and organic debris carried by runoff continue to flow downslope and are likely retained by lower slope terraces. The permeability of terraces has a strong influence on the amount of runoff retained. As terrace walls become breached they become less efficient. If people wanted more efficiency they could alter these conditions by adding brush, more stones, soil berms, etc. Those specific behaviors leave no archaeological trace but it is possible that people influenced efficiency. Below I discuss how efficiency rates above 30% influence the simulated nitrogen fluctuations.

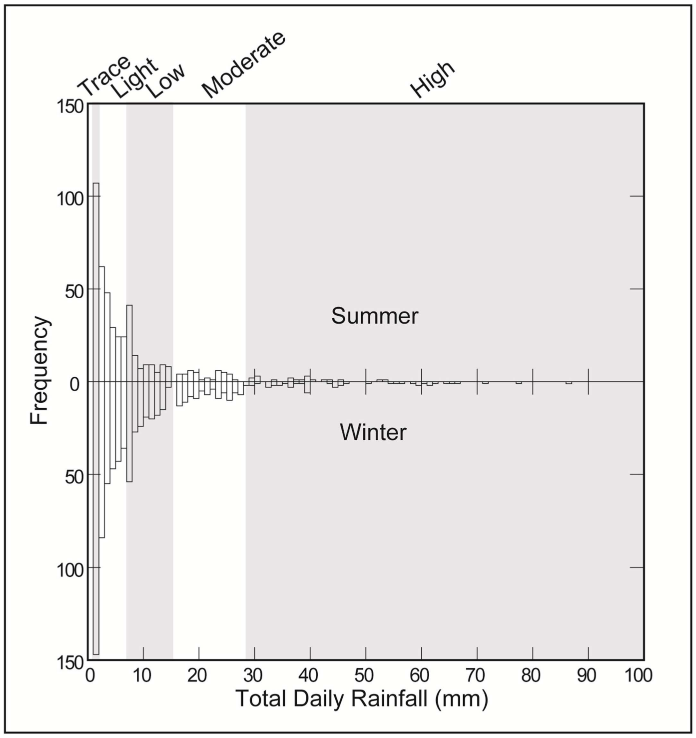


Figure 7.1. Rainfall categories and the frequency of daily rainfall amounts from the Sunset Point 5730 weather station (7/1/1981-9/30/2010).

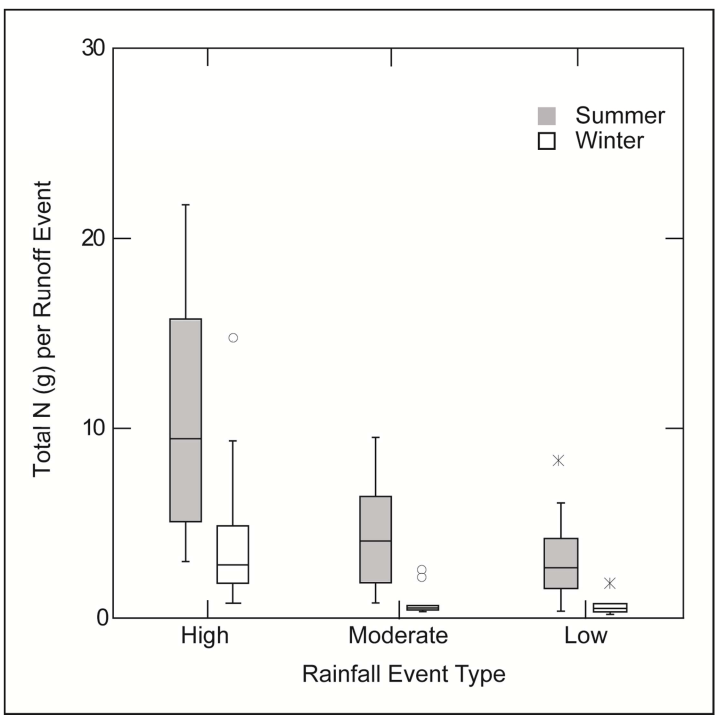


Figure 7.2. Box plots of total N (g) per rainfall category.

Table 7.6. Values for total nitrogen of runoff sediments.

			Total Nitrogen Pool (g) of Runoff Sediments		
			Low	Median	High
Rainfall Event Type	High *(a)*	S	5.26	10.29	17.24
		W	1.83	2.82	4.86
	Moderate *(b)*	S	1.88	4.10	5.89
		W	0.51	0.61	1.00
	Low *(c)*	S	1.59	2.67	4.19
		W	0.37	0.51	0.70

Table 7.7. Total nitrogen values for $r_{a, b, c}$. Assumes only 30% of the total runoff pool is retained within terraces.

			r		
			Low	Median	High
Rainfall Event Type	High *(a)*	S	3.68	7.20	12.07
		W	1.28	1.97	3.40
	Moderate *(b)*	S	1.32	2.87	4.12
		W	0.36	0.43	0.70
	Low *(c)*	S	1.11	1.87	2.93
		W	0.26	0.36	0.49

Much of the nitrogen in runoff is tied up in organic forms of fresh detritus that require mineralization before they can be made available for plants (Lister 2007; Sandor et al. 2007). This is why the proportion of inorganic N to TN can actually be lower in runoff sediments compared to surface soils (see Lister 2007). Nitrogen recently deposited by runoff is relatively immobilized and may not be available in the short-term but will be in the long-term as decomposition occurs to break down runoff debris (Thomas and White 1999 in Sandor et al. 2007). Runoff deposition will have a more long-term influence on nitrogen pools than an immediate effect on plant uptake.

The proportion of nitrogen in runoff sediments that is in plant-available inorganic forms was not measured directly in this study due to lack of remaining sample sediments from individual samples to conduct inorganic N analysis (ca. 10 g). Estimates of the inorganic nitrogen proportions were derived from a similar runoff study in the grassland and shrublands of the Jornada region in central New Mexico (Lister 2007), a similar environment to Perry Mesa. Ratios of inorganic N to TN in runoff sediment derived from rainfall simulations in 1-m^2 plots ranged from 0.3% to 5.0% (Lister 2007: Table 7.1[1]). The ratio is largely dependent upon when the runoff is derived relative to other runoff events. The first event of the season may have more fresh detritus but over time this detritus is flushed away and later events will have higher available nitrogen as organic debris breaks down. Based on these data from another region, a flat rate of 1.5% was assumed to be the proportion of TN in runoff sediment that is inorganic nitrogen and therefore available for plants (Table 7.8). Therefore, the remaining 98.5% of runoff-transported nitrogen is assumed to contribute to the overall TN pool available to be mineralized in future time steps.

Table 7.8. Values for $r_{a,b,c}$ after mineralization rates applied.

			$(r)\beta_r$		
			Low	Median	High
Rainfall Event Type	High $(_a)$	S	0.06	0.11	0.18
		W	0.02	0.03	0.05
	Moderate $(_b)$	S	0.02	0.04	0.06
		W	0.01	0.01	0.01
	Low $(_c)$	S	0.02	0.03	0.04
		W	0.00	0.01	0.01

Based on the estimated values for *r,* it is clear that individual runoff events contribute minimal amounts of immediately available nitrogen. As calculated below, a maize hill with 4 plants may uptake as much as 44.12 g of nitrogen (Table 7.6). However, the accumulation of nitrogen for future availability via mineralization may be significant. Simulations presented in the following section address the short and long-term benefits of nitrogen deposited by runoff.

Number of Runoff Events per Precipitation Regime (x)

In order to estimate the number of runoff events that would likely occur during each time step of the model, 1 year, paleoclimatic and historic weather station data were integrated. Based on dendroclimatological data, Ingram (2009) estimated annual precipitation levels in central Arizona from A.D. 570-1987. He also classified each year as part of a wet, average, or dry climatic regime based on 9 year running averages. Paleoclimatic records lack the resolution to determine how many of different types of rainfall events (high, medium, low) occurred within a year, and therefore cannot be used to reconstruct frequency of runoff events in the past. However, historic weather station data provide information about annual precipitation as well as daily precipitation records. Therefore, historic information was used to estimate the frequency of different rainfall event types that would have likely occurred under the three climatic regimes.

The climatic classifications (wet, average, dry) determined by Ingram (2009) were applied to the annual precipitation data for the Cordes (022109) weather station available from the Western Regional Climate Center (www.wrcc.dri.edu; Table 7.9). The Cordes weather station is located 15 km north of Perry Mesa at a similar elevation (1150 m). Other stations, such as Sunset Point and Horseshoe Ranch, are located on Perry Mesa but

Table 7.9. Dry, average, and wet climatic periods and average annual precipitation for the Cordes weather station.

Climatic Classifications	Historic Periods	Avg. Annual Precipitation
Dry	1949-1974	13.65
Average	1975-1978, 1984-1987	15.21
Wet	1979-1983	20.78

lack the time depth of the Cordes station. The Cordes station has over 50 years of recorded historic data, whereas stations on Perry Mesa have only 20. For the last 21 years when the Cordes and Sunset Point records overlapped, the Cordes annual precipitation was higher by 3-4 inches approximately 2/3 of the time and the Sunset annual precipitation was equal or higher by 2-4 inches 1/3 of the time. Similar trends were observed between the Cordes and Horseshoe Ranch stations. Despite the slightly higher average annual precipitation observed at the Cordes weather station, the timing of precipitation and types of events tracks well with stations on Perry Mesa and therefore it was used to determine the frequency of rainfall event types likely to occur during climatic regimes.

The rainfall event types followed the previously established rainfall categories of high, moderate, low, no runoff, trace, and none. The frequencies of rainfall events that would likely produce runoff, the high, moderate, and low categories, are the focus of this analysis. As explained above, these types of rainfall events produced different runoff conditions in summer and winter and therefore the seasonal distinctions are maintained. Rounded averages of the frequencies of each runoff event type during summer and winter were determined for dry, average, and wet precipitation regimes for the Cordes weather station. These averages serve as the value for *x* in the simulation model (Table 7.10).

The frequency of different types of rainfall, and subsequent runoff, events follows general expectations with dry climatic regime years having fewer occurrences of all rainfall event types than average and wet years. Average and wet years have similar event frequencies, with the exception of high events. Wet years are more likely to have more high-yielding rainfall events, in summer and winter, than either dry or average years. This is most likely what is driving the determination of these years as "wet" rather than the frequencies of moderate and low rainfall events which are similar to those in dry and average years.

Table 7.10. Number of expected runoff events by precipitation regime (*x*).

Precipitation Regime	**Number of Runoff Events Expected *(x)***						
	High Runoff (r_a)		Moderate Runoff (r_b)		Low *Runoff* (r_c)		Total Yearly Events
	S	W	S	W	S	W	
Dry	1	1	2	2	4	4	14
Average	1	1	2	3	5	7	19
Wet	2	3	1	4	3	6	19

Summer (S) =J, J, A, S and Winter (W) =O, N, D, J, F, M, A, M.

Maize Nitrogen Needs (M)

Maize nutrient uptake is a complex dynamic based on total nutrient pools of soil, moisture, temperature, root depth, variety, and growth stage. Therefore, the amount of nutrients taken up by a maize plant can be highly variable (Olsen and Sander 1988). Unfortunately there is very little information about nutrient uptake for traditional varieties of maize and estimating nitrogen needs can be difficult. However, several current studies are providing relevant information. Nutrient concentration data from field growth experiments of traditional maize in the Zuni area (Jonathan Sandor, personal communication) provided the basis for the maize nitrogen needs parameter used in this simulation model. The concentrations of nitrogen in the dry weight of maize grain and in maize biomass were used to estimate the grams of N taken up per maize plant (Table 7.11). Data were based on 30 samples of Zuni blue maize grown under natural rainfall conditions, within a field where runoff water was applied, and a field where runoff water plus associated sediments were applied. The Zuni experiment also grew maize under irrigation and commercial nitrogen conditions, resulting in much higher maize grain and biomass nitrogen concentration rates. Only the rainfall and runoff field conditions were considered here because these growth conditions were most similar to the prehistoric conditions on Perry Mesa.

A hybrid maize variety was also grown under the same conditions as the traditional Zuni variety. The total N content of the hybrid maize (grain and biomass) was similar in total nitrogen content to the Zuni variety; however, the nitrogen content of just

Table 7.11. Nitrogen content of Zuni blue maize. Data from J. Sandor (personal communication).

	N content of maize grain (g/plant)	N content of maize biomass (g/plant)	N content of maize grain and biomass (g/plant)
Low	0.95	3.93	4.71
Median	1.35	5.92	7.20
High	2.02	9.57	11.03

the grain was higher for Zuni maize indicating traditional varieties may be more efficient at mobilizing nitrogen for grain production (Sandor et al. 2007). Nitrogen content values for the hybrid variety exhibited a smaller range of variability than the traditional variety (Sandor et al. 2007), reflecting the selective pressures to reduce diversity in hybrid maize.

Recent discussions of prehistoric nitrogen uptake of maize on the Colorado Plateau assumed a value of 3.3 g N per maize plant (Benson 2011b) based on N concentrations in grain, cobs, and stover (stalks and leaves) in modern maize hybrids (Shinners and Binversie 2007; Sawyer and Mallarino 2007). This estimate is below the per plant nitrogen uptake values used here, but given the high variability of traditional varieties it may be appropriate as a conservative estimate.

Based on traditional maize planting strategies, it is assumed that several maize plants are located within a single planting hill. Southwestern ethnographic accounts document that as many as 15 or 20 seeds are planted per hill and the smallest plants were later removed resulting in a few stalks per hill, usually four or five, (Bradfield 1971; Clark 1928; Cushing 1920; Forde 1948; Hill 1938). The experimental design of the Zuni study, where the nitrogen content data were derived, called for 6 maize kernels per hill based on traditional Zuni planting strategies. Approximately 4 plants per hill reached full maturity (Jonathan Sandor, personal communication). An estimate of 4 maize plants per planting location was used in the simulation model. Maize is wind-pollinated and the close spacing of at least 4 plants is likely necessary for good pollination. As discussed above, it is assumed that planting hills are placed every 2.3 m. The nitrogen uptake per planting hill estimates are presented in Table 7.12.

Table 7.12. Values for *M* (after J. Sandor, personal communication).

	M
	Grain and Biomass
Low	18.84
Median	28.8
High	44.12

The Models

Two versions of the model were simulated, one under conditions of no runoff, or a strictly dryland system, and one under conditions of nitrogen-contributing runoff. Nitrogen fluctuations under cultivation without considering runoff were simulated based on the following:

$$I_t = (N_t \beta_s)$$
$$E_t = \frac{I_t - M}{\alpha_{a,b,c}}$$
$$N_{t+1} = (N_t - I_t + E_t)$$

When runoff was considered in the simulations, N was calculated as the following:

$$I_t = (N_t \beta_s) + ((r_a x + r_b x + r_c x)\beta_r)$$
$$E_t = \frac{I_t - M}{\alpha_{a,b,c}}$$
$$N_{t+1} = (N_t - I_t + E_t) + \left[(r_a x + r_b x + r_c x)(1 - \beta_r)\right]$$

The amount of inorganic nitrogen, the plant available nitrogen, is represented as *I,* and the total nitrogen pool is represented as *N.* Mineralization rates, the proportion of nitrogen that is converted into plant available forms, are designated as β with subscripts *s* and *r* indicating soil and runoff respectively. *E* represents the amount of inorganic nitrogen that is retained after each time step *(t)* after the maize nitrogen needs *(M)* are met based on the proportion of inorganic nitrogen *(α)* retained, denoted with subscript *a* (0%), *b* (50%), or *c* (100%). The nitrogen carried by runoff events is represented as *r* depending upon the type of runoff event denoted as subscript *a* (high), *b* (moderate), *c* (low). The number of each type of runoff event is represented as *x*. Visual representation of the simulation model is presented in Figure 7.3.

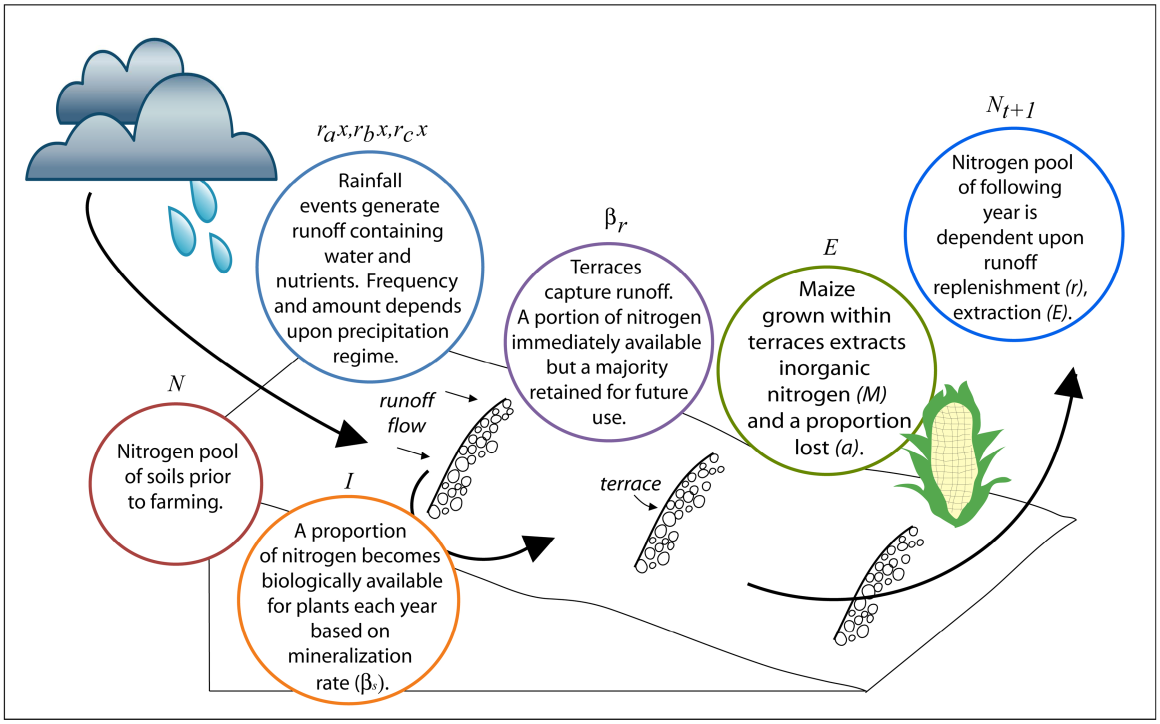


Figure 7.3. Schematic representation of the simulation model.

The model parameters estimate nitrogen fluctuations under maize cultivation for a soil surface area of 2.3 m and a depth of 40 cm based on the spacing of maize hills every 2.3 m, approximately 3-4 paces, in traditional dryland farming in the Southwest (Bradfield 1971; Brown 1952; Cushing 1920; Manolescu 1995) and soil profiles depths from excavations within the Bull Tank Agricultural Field (Chapter 4) and the likelihood of deflated A horizons over the past few centuries. The spacing of planting hills is based upon the need to place plants at wide distances to maximize limited water availability. It is assumed that prehistoric dryland farmers on Perry Mesa practiced similarly wide plant spacing. The 2.3 m area is also similar to the amount of cleared space behind individual agricultural terraces in the region.

Model Results and Discussion

The model was run using different configurations of variable states. Changing one variable's values in the model runs makes it possible to see how the model responds to variation to determine which variables are responsible for driving model results.

Maize Pressures on Soil Fertility

Soil fertility fluctuations were simulated for strictly dryland conditions, meaning rainfed conditions with no supplemental runoff and therefore no supplemental nutrients deposited (Figure 7.4). Soil provides the only nutrient source during these simulated conditions. The y-axis of the figure shows the amount of inorganic N available and time is displayed on the x-axis. The dashed lines represent the low, median, and high estimates used for the amount of nitrogen necessary for maize. When the amount of simulated inorganic N, the colored lines in the figure, dips below the dashed lines, there is not enough available N to support the maize needs for each estimated level. Each group of lines represents the simulated mineralization rates, either 1.5%, 1.0% or 0.5%. Each line within each group assumes a different amount of excess inorganic nitrogen is retained, or carried over, to the next time step or year.

The amount of inorganic N retained each year appears to have little influence on the overall pattern of inorganic N. Rates of inorganic N decline faster when none of the

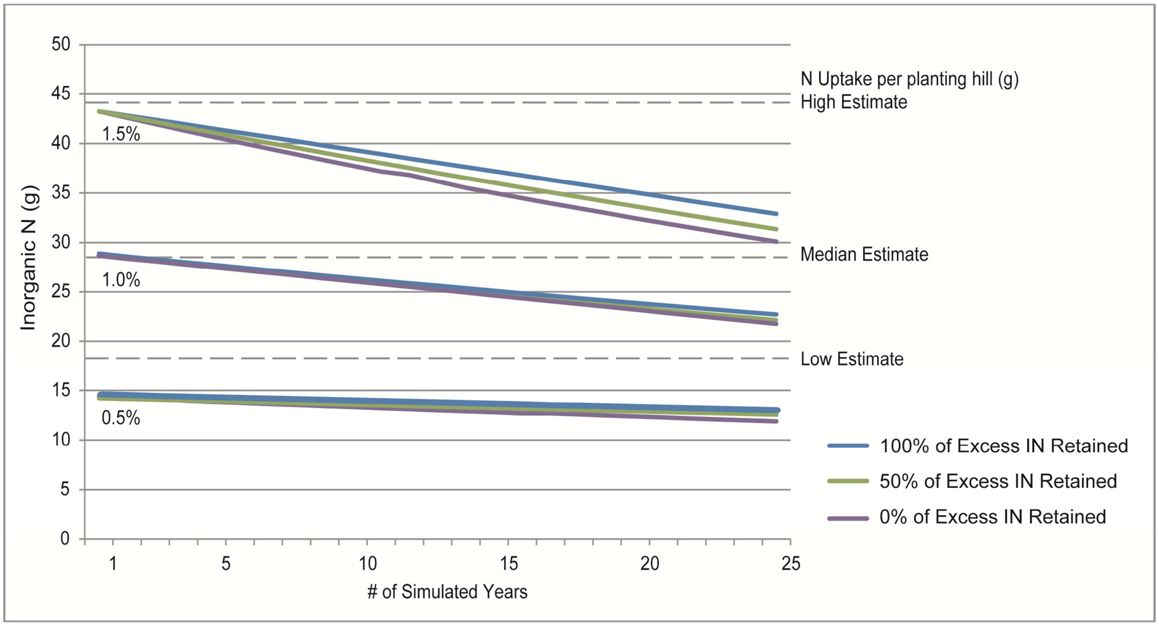


Figure 7.4. Inorganic nitrogen *(I)* levels of simulated maize cropping system. Parameters were based on the medians for values for the total nitrogen *(N)* variables. Inorganic N fluctuations shown for annual mineralization rates (β_s) of 1.5%, 1%, and 0.5%. Estimated nitrogen needs shown with dashed lines.

excess nitrogen is retained and slower when all (100%) of the excess inorganic N is retained.

Results show that maize nitrogen needs are only met when maize needs are assumed to be low, and nitrogen mineralization is above 0.5%. An annual mineralization rate of 1.5% easily supports the extraction needs for the median and low estimate of maize needs for extended periods of time (ca. 25 years). However, if maize extraction exceeds the median values of estimated inorganic N maize needs (the high estimate), a 1.5% mineralization rate cannot support the inorganic N needs of a maize planting hill for any amount of time. An annual mineralization rate of 0.5%, a realistic estimate for Perry Mesa conditions, never supports the maize grain and biomass needs even if estimates of that need are low. A mineralization rate of 1% can only support the median estimate of maize needs (28.8 g of inorganic N) for 1 year before inorganic N levels fall below this value.

Field life easily exceeds 25 years if 2.5 or 3.5% annual mineralization rates are achieved (not shown). However, as previously stated, higher mineralization rates may be unattainable for the semiarid conditions on Perry Mesa and therefore are likely overestimates of field use life. It is more accurate to assume median estimates, a 1% mineralization rate for soil nitrogen, and a maize extraction need of 28.8 g IN. Under these conditions maize needs are only met for 1 year.

Therefore, under the assumed cultivation practices of 4 plants per hill and nitrogen needs similar to contemporary Zuni blue corn, corn cultivation in this model would be unlikely or difficult for more than one year. Fewer plants per hill or maize varieties with lower nitrogen needs would be the only way that production would be possible under the conditions of the region. Additional nutrient inputs, such as runoff, could have been a possible solution to provide enough inorganic nitrogen for higher maize nitrogen needs. In fact contributions from runoff would have been *necessary* for cultivation to occur under the assumed spacing and density.

Runoff Additions to Soil Fertility

Soil fertility fluctuations were also simulated to include nutrients from runoff (Figure 7.5). Similar to the simulation that did not consider runoff presented above, results indicate that that maize nitrogen needs are only met when maize needs are assumed to be low, and nitrogen mineralization is assumed to be higher than 0.5%. However, the rate of nitrogen depletion (the slope of the lines in the graph), is less than when no runoff nutrients are considered.

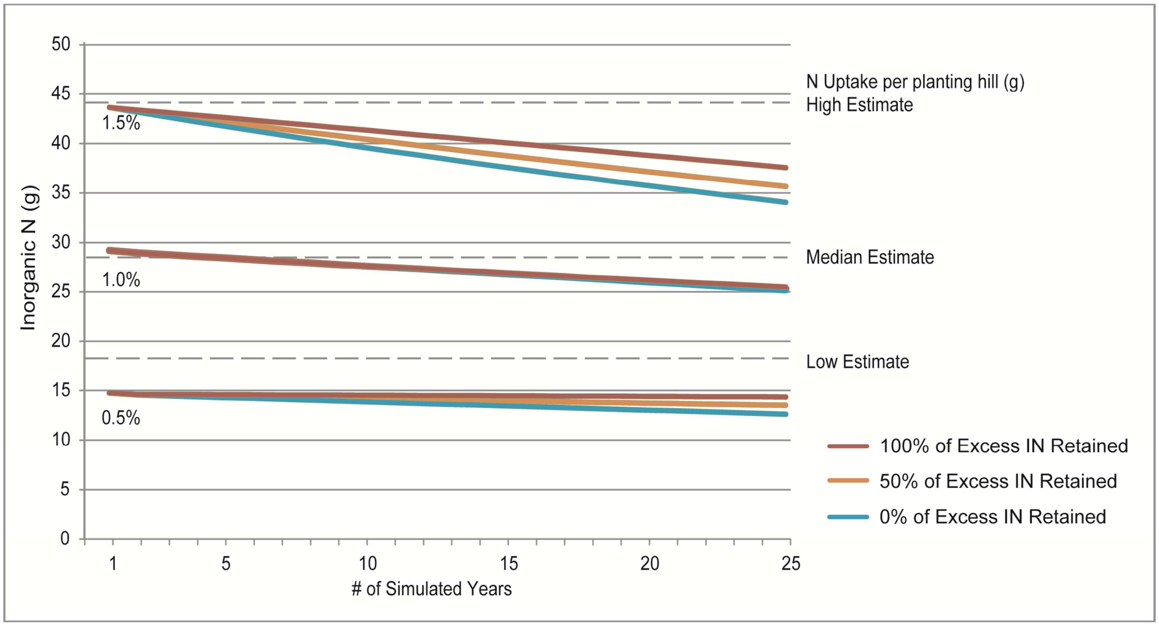


Figure 7.5. Inorganic nitrogen *(I)* levels of simulated maize cropping system with runoff retention. Simulation parameters were based on the median values for the total nitrogen *(N)* and runoff (*r*) variables. Thirty percent of runoff (r) was assumed to be retained. Values for N uptake per planting hill shown with grey shading and simulated annual mineralization rates (β_s) are identified as 1.5%, 1%, and 0.5%.

Figure 7.6 presents a simulation comparing dryland with runoff conditions. The point at which the inorganic N levels fall below the maize needs, shown by the dashed line, is interpreted to indicate the point at which the maize nitrogen needs are no longer met. This point occurs after just one year in strictly dryland conditions and runoff conditions but the rate of decline is less when runoff is considered. The slower rate of nitrogen decline under runoff conditions means that fields can be farmed for longer periods of time.

When the terrace runoff retention efficiency rate is estimated to be higher than the 30% value, the rates of inorganic N decline are even slower (Figure 7.6). A higher efficiency rate means more of the nitrogen transported by runoff is retained. When rates

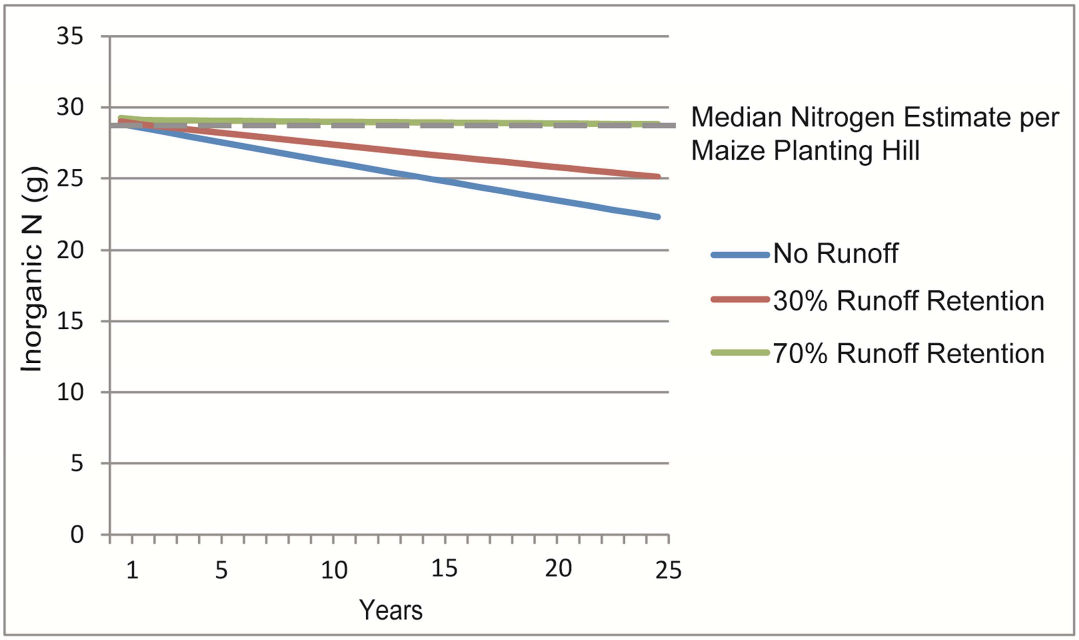


Figure 7.6. Comparison of inorganic nitrogen rates of decline under no runoff, 30%, and 70% runoff retention.

are assumed to be 70%, inorganic nitrogen levels remain steady indicating that fertility is maintained over long periods of time, >25 years. If people took steps to make terraces more efficient, field use life could be prolonged or even used almost indefinitely. However, this efficiency would prevent downslope areas from receiving runoff requiring field systems to be smaller. Also, increasing terrace efficiency would not be without consequences, as more labor for repair and monitoring would be necessary. Having watched many runoff events within the Bull Tank agricultural system, it would be relatively easy to pile up brush or stones in certain places during a storm to increase sediment deposition. This would however mean that farmers would have to constantly be observing their fields, not difficult, but requiring more time and investment. Demands would be higher because both active and inactive fields would need to be managed. The predominance of small farmsteads and field houses may explain these labor demand needs of Perry Mesa farmers. Extended stays within agricultural lands would facilitate the maintenance of runoff management for both active and fallowed fields.

The 30% retention efficiency rate is considered to be a realistic, albeit likely conservative, estimate for the amount of runoff retained in each individual terrace. Overall, an entire terrace system would likely have a higher runoff efficiency rate with most of the runoff captured somewhere within the system. The simulation, however, considers nitrogen dynamics at a small spatial scale of a single maize planting hill in one terrace feature.

A closer look at the temporal influence of runoff on soil fertility indicates that runoff has more influence on the long-term than the short-term or immediate simulated time-step. Each annual contribution of inorganic nitrogen from runoff contributed only a small proportion of maize needs during that planting cycle, 0.09 - 0.28 g, less than 1% or the total needs of 18.84 - 44.12 g (Table 7.13). As discussed above, the simulation assumes that only 1.5% of the nitrogen transported by runoff is immediately available as inorganic nitrogen. The impact of runoff is negligible in the first year but its impact is pronounced as the simulation moves forward in time. Overall each year of runoff contributes between nearly 6 – 19 g of nitrogen.

Table 7.13. Nitrogen estimates used in the simulation model.

Precipitation Regime	Nitrogen Need of Maize Hill (g)	Annual Total of IN from Runoff (g)*	Annual Total of N from Runoff (g)**
Average	18.84-44.12	0.09-0.28	5.91-18.82

*Available for the immediate time step.
**Potentially available in future time steps.

Influence of Climate Regime on Soil Fertility

The number and intensity of runoff events depends upon the climatic regime (Table 7.10), and thus the amount of deposited nitrogen is also influenced by the climate (Table 7.14). For example, although wet climate regimes are estimated to have the same number of runoff events as average climate years, they have more high intensity runoff events leading to more nitrogen deposition during these periods.

Table 7.14. Amount of estimated total nitrogen deposited per year during different climatic regimes. Estimates assume 30% of runoff is retained per planting area.

	Total Nitrogen Pool (g) of Runoff Sediments		
Regime	Low	Median	High
Wet	8.08	14.0	22.72
Average	6.88	12.02	18.82
Dry	5.91	10.58	16.63

The rates of depletion of IN under cultivation are similar between wet, average, and dry climatic regimes when only 30% of runoff is retained (Figure 7.7). Rates of depletion are only slightly slower during wet regimes compared to average and dry due to the higher amounts of total nitrogen in runoff sediments. However, when more runoff is assumed to be retained, i.e. 70%, nitrogen actually *increases* even under cultivation (results not shown) when the modeled climate is assumed to be wet and the highest estimates for nitrogen-related variables and the lowest maize nitrogen estimates are used. Therefore, it can be concluded that under optimal conditions (high nitrogen, wet climate, high runoff retention in terraces, low maize needs) there is opportunity for nitrogen conditions to improve over time when cultivation is occurring. This eliminates the need for fallow.

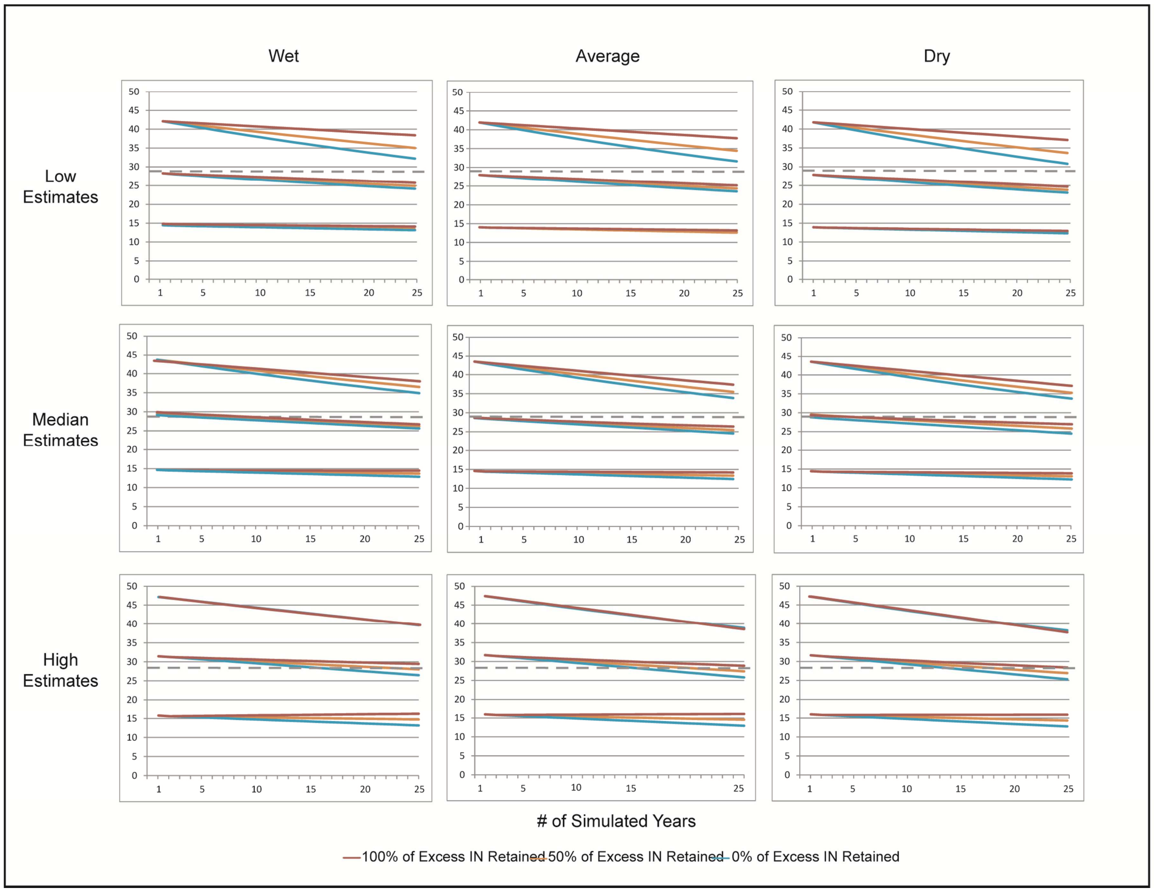


Figure 7.7. Inorganic nitrogen levels of simulated maize cropping system with 30% runoff retention for wet, average, and dry precipitation regimes. Median estimate for N uptake per planting hill shown with dashed line.

All other modeled conditions, however, would require fallow periods without cultivation for nitrogen levels to recover. Management of runoff during fallow is a good way for this renewal to happen more quickly, as rates of decline are slower during cultivation with runoff compared to strictly dryland conditions.

In order to determine how long fallow periods would need to be to bring nitrogen to pre-cultivation levels, simulations were completed for 2, 5, and 10 year periods of cultivation followed by fallow periods where runoff was accumulated. The year where IN levels recovered to the pre-cultivation value was concluded to be the number of years of necessary fallow (Table 7.15). The results indicate the proportion of the landscape that is under production and the proportion that should in recovery or fallow.

During wet regimes, inorganic N levels recovered much more quickly than during dry regimes. For example, if a field was farmed for 5 years, recovery would take 6 during wet climate regimes, 8 during average, and 10 during dry climate regimes. This is due to the fewer runoff events, particularly high intensity events, that occur during dry years (see Table 7.10). This indicates that during dry years, compared to wet or average, more land would be in fallow and not producing crops.

Table 7.15. The number of years under cultivation to years in fallow with runoff incorporated into the nitrogen pool. Model variables are based on the median estimates for nitrogen related parameters and maize extraction.

	Estimated # of Years of Fallow		
Estimated # of Years Cultivated	Wet Climate	Average Climate	Dry Climate
2	3	4	5
5	6	8	10
10	12	15	19

If a significant proportion of land was in fallow and needing runoff management, more labor would be going towards delayed returns than crop production. This has real consequences for the amount of land producing food and the total amount of land necessary per household to meet basic caloric needs. In other words, 45% of the managed agricultural land would be returning food in wet regimes, 38% in average, and only 33% during dry. The remaining proportion of land would need to be managed to return nutrient levels but would not be immediately returning food.

The climate dynamics influence not only fallow recovery but the availability of precipitation for crop growth. Long fallow recovery coupled with precipitation stress, would make farming extremely difficult during dry climatic periods, particularly if they were prolonged. However, wet climatic regimes would improve farming conditions. Not only would there be the greater amounts of precipitation, but fields would have longer use lives and fallow recovery periods would be shorter due to the increased frequency of large runoff events. The "good times" during wet precipitation regimes might also be essential to provide buffers for period short-term dry periods lasting a few seasons.

Conclusions

Based on the model results, several conclusions can be drawn. First, soil nitrogen input from runoff was necessary in this region. Second, fallowing fields was likely critical for renewing soil fertility. Third, under dry climate conditions the amount of labor needed to manage untilled fields and to farm sufficient land for an adequate crop may exceed the labor available.

Fertility declines are far less rapid when nitrogen from runoff is included, but declines still occur. Runoff maintenance during fallow periods would improve fertility conditions more quickly. Fields integrating runoff sediments could likely be cultivated for approximately 3 years before the fallowing is necessary. The amount of time fields are required to be fallow to bring nitrogen to pre-cultivation levels increases depends upon the length of time fields were cultivated and the climatic regime. The period of cultivation to fallow increase the longer fields are originally cultivated.

Soil nutrient dynamics, particularly the frequency and amount of runoff renewal events, are dependent upon the climate regime. When runoff is considered, nutrient declines are slowest during wet climate regimes and faster during dry regimes due to the frequency and amount of expected runoff event. This influences the amount of time land can be cultivated and shortens the length of necessary fallow to return fertility to pre-cultivation levels. For example wet climatic regimes have the potential to shift the landscape from marginal conditions, in terms of fertility, to good due to the greater amount and frequency of runoff renewal events. Although not directly considered in the model, wet climatic regimes are also better for agricultural production due to greater moisture. This could increase surplus production allowing for a buffer during dry conditions as well as decrease the demand for arable land as less land per household is necessary. During dry climatic regimes the amount of labor needed to manage fallowed fields and to farm sufficient land for an adequate crop would be high. It is possibly that it would be too high to make sense to remain in the region. Even if labor were available, there may not have been enough land available, a point addressed in the next chapter.

The extensive distribution of terrace agricultural features on the Perry Mesa landscape is indicative of soil and runoff management strategies aimed at maximizing runoff potential and soil fertility. The widespread use of these features is not interpreted to indicate Perry Mesa farmers were producing an abundance of agricultural crops but rather that they used these features in order to farm this landscape for more than a single planting cycle. Perry Mesa farmers harnessed the nutrient renewal potential of surface runoff by constructing features. Chapter 8 discusses whether the agricultural land available, including the amount of improved terraced land, would have been adequate given the landscape of Perry Mesa, population size estimates, and cropping/ fallow ratios discussed above.

Chapter 7 Notes

[1] Lister (2007) also monitored runoff in plots dominated by mesquite vegetation. Because mesquite is not currently dominant on Perry Mesa, nor was it in the past, data from these plots were not considered.

Chapter 8:

CHARACTERIZATION OF THE PREHISTORIC AGRICULTURAL LANDSCAPE AND LAND USE REQUIREMENTS

The results of the runoff collections and simulation model of maize growth are useful characterizations of runoff agricultural conditions on Perry Mesa. However, they do not directly inform us about the prehistoric conditions that were experienced by ancient populations living in the area at specific periods of time. The focus of this chapter is a characterization of the agricultural landscape during the Perry Mesa Tradition (PMT, A.D. 1275 – 1450), the population height of the region.

Previous research has demonstrated that the beginning of this period was climatically favorable for agricultural expansion into the region based upon temperature and winter precipitation reconstructions (Ingram 2009, 2012, 2013). The addition of the soil and runoff collection information (Chapters 6) and simulations of soil fertility cycles (Chapter 7) provides a richer understanding of agricultural potential in the region beyond considerations of climate alone.

The assessment of agricultural potential for the PMT period presented here combines paleoclimatic information with the results of long-term maize growth simulations as well as landscape information about the amount of potentially arable land and land use requirements based on population reconstructions. The amount of potentially arable land was estimated from a GIS model integrating slope, watershed size, and factors influencing soil availability. The amount of land required for agriculture was determined by integrating ethnographic information and the cropping/fallow ratios calculated with the maize growth simulations in Chapter 7. Population estimates rely upon surface room counts for sites identified as PMT period that have been documented in systemically surveyed areas on Perry Mesa.

Together these data are used to determine if there was enough productive land available to support the suggested crop-to-fallow rates required to maintain soil fertility. Available paleoclimatic reconstructions (Ingram 2012) are used to determine which portions of the PMT time period would have been good contexts for agricultural expansion or possible stress periods.

Ingram (2012) identified a particularly favorable 16 year-long wet period during the early 1300s. Based upon the results of the simulation model, it is inferred that this was a period of time when less land was necessary to support cropping/fallow cycles and land surpluses were at their greatest. Ingram (2012) also identified more frequent and long-lasting dry periods during the end of the 15^{th} century occupation, possibly influencing depopulation of the region. Similarly, it is inferred that these dry periods are when potentially arable land deficits would be at their greatest, causing stress on maintaining cropping/fallow cycles.

Potential Arable Land Estimate

Previous analyses (Kruse 2007) of the location of runoff agricultural terrace features identified during archaeological surveys on Perry Mesa (Gumerman et al. 1975; Kruse 2005; North 2002) and of landscape settings of similar features throughout the Southwest (Dominquez 2002; Homburg 1997; Sandor 1995; Sandor et. al. 1990; Sullivan 2000; Wells 2003; Woodbury 1961) resulted in a map of the quantity and distribution of potentially arable land on Perry Mesa. Fields with agricultural features controlling runoff are the locations where most agricultural production would have occurred on Perry Mesa.

The main criteria used to identify potentially arable land relate to topography and conditions that create surface runoff flows, but flows that are not high in quantity or velocity, which would wash out fields causing erosion or damage to crops. Runoff agricultural features are located on gentle slopes of 1-10 percent and within small watersheds of less than 10 hectares. While the upland areas of the region are classified as a mesa, there are gentle rolling hills across the area. Flat areas (<1 percent) are found in patches throughout the area with steeper slopes (>10 percent) located primarily within the steep canyons. Flat parcels of land would not have produced runoff necessary to supplement rainfall and renew soil fertility. These areas, however, are dominated by rock pile features associated with agave production (Kruse-Peeples 2013). The region is characterized by small watersheds of less than 1 hectare with larger catchments (>10 ha) existing at the bottoms of the steep canyons of the Agua Fria River and side tributaries. The slope criterion eliminates most of these larger catchments.

Slope aspect or orientation has been discussed as an important factor for field placement in some locations due to the moisture retention qualities of northern slopes or heat retention qualities of southern exposures (Woodbury 1961). However, no preferential placement of fields with respect to aspect was observed and therefore it was not used as a criterion to identify arable land (Kruse 2007).

Soil is also an important factor in field placement and availability of soil was used as criterion for identification of potentially arable land in this study. Detailed soil characterization of the Perry Mesa region is lacking. Existing landscape scale data classify soils on the mesa tops within the Springerville-Cabezon complex (fine, montmorillonitic, mesic Aridic Haplusterts) and soils in the canyon areas are classified within the Rimrock-Graham complex (fine, montmorillonitic, thermic Typic Chromusterts; Wednt et al. 1976). Both complexes are vertisols based on the high content of expansive clay known as montmorillonite that forms deep cracks in drier periods. Based on landscape scale data alone it is difficult to determine which locations were better for agriculture based on spatial variation in soil qualities such as moisture retention, fertility, or soil depth. What is clear from observing the landscape is that there are some patches of land that are dominated by bedrock outcrops and large boulders. These locations lack exposed soil in which crops can be planted. A map of soil availability was created based on LANDSAT images with Multi-Spec image analysis software. The spectral signature of known bedrock outcrop areas was used to identify other probable bedrock outcrops within the study area. Areas identified as bedrock outcrops were eliminated as potentially arable with remaining land classified having soil.

A map of potentially arable land was created for the 500 square kilometer study area that encompassed all of Perry and Black Mesas (Figure 8.1). Similar to other assessments of agricultural land (Dorshow 2012; Hill 1998; Schollmeyer 2009), potentially arable land was determined by overlaying raster layers in ESRI ArcGIS software. Parcels of land that met all criteria (slopes less than 10 percent, watersheds smaller than 10 ha, and soil available based on lack of bedrock) were determined to be potentially arable and areas that did not meet all 3 criteria were eliminated. In addition to the LANDSAT images mentioned above, Digital Elevation Models (DEMs), raster based elevation maps, were obtained from the U.S. Geological Survey. The 30 m DEM data were used to match the resolution of LANDSAT data. Therefore, the pixel sizes of the resulting map were 30 x 30 m. Slope and watershed size were derived from the DEM data.

Admittedly the resulting map is of coarse resolution. The analysis does not hierarchically categorize arable land from most suitable to least suitable in the region. In reality farmers would have had intimate knowledge of specific niches that may have been the best land, which locations needed improvement with landscape modifications, and those parcels that should be avoided. The analysis, however, is intended to be at a broad landscape scale to determine the quantity and distribution of potentially arable land based on general requirements for runoff agricultural strategies.

Population Estimates

Population estimates for the region are based on surface masonry room counts rather than the identification of individual household suites or a cluster of rooms that contain domestic facilities architecturally separated from adjacent households. The data available for Perry Mesa sites are predominately derived from surface architectural remains and associated artifact scatters, as few sites have been excavated or well-mapped. Determining occupation lengths or construction dates of individual sites or rooms is not possible given current data. No dendrochronological information from construction beams currently exists. In fact, very few other absolute dates have been recovered from the area (Fiero et al. 1980; Spoerl and Gumerman 1984) leading to very coarse dating resolution relative to other data which are available in a finer resolution, such as the paleoclimatic reconstructions. The population estimate, therefore, represents the maximum population living on Perry Mesa during the late 13th into the 14th centuries.

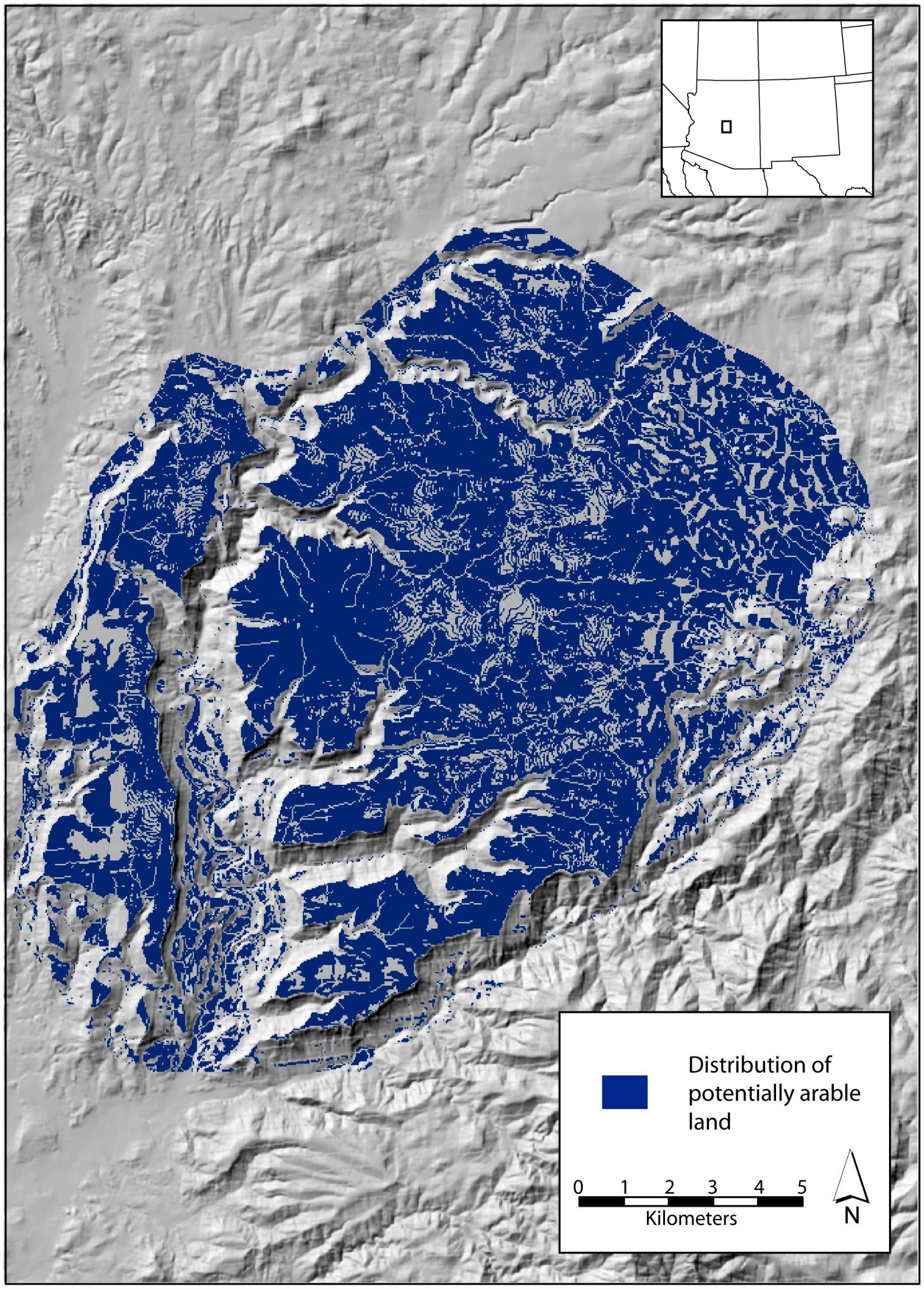


Figure 8.1. Distribution of potentially arable land on Perry and Black Mesas.

Assigning sites to time periods is based upon the presence of diagnostic ceramics. This can be difficult due to the quality of some survey data as some records lack descriptions of artifacts. Moreover, many sites also lack the presence of diagnostic ceramics. Decorated assemblages associated with PMT sites are dominated by Salado Polychromes, Hopi yellow wares (Awatovi Black-on-yellow and Jeddito Black-on-yellow), and occasional sherds of Sikyatki Polychrome or White Mountain Redwares. PMT plainwares include Tonto Plain and high-luster, polished redwares. The PMT assemblages are distinct from earlier period ceramics which are dominated by Wingfield plainwares, phyllite-tempered plainwares, and Little Colorado whitewares the predominant decorated ceramic (Kruse-Peeples and Strawhacker 2012; Sporel and Gumerman 1984; Wood in review).

A database of all currently recorded sites in the Perry Mesa area was created from existing archaeological survey records (Ahlstrom et al. 1992; Baker and Bruder 2002; Douglas 1994; Billsbarrow 1007; Billsbarrow et al. 1997; Fiero et al. 1980; Fish et al. 1975; Gumerman et al. 1975; Huett and Long 1996; Kruse-Peeples et al. 2009; North 2003; Watkins 2012; Wilcox et al. 2001b: Appendix 7.1; Wilcox and Holmlund 2007) and AZSITE records. A total of 594 prehistoric sites was included in the database, 426 of which included surface masonry structures (Kruse-Peeples and Strawhacker 2012). Information recorded about each masonry site included a room count estimate or range of estimated rooms based on the estimate presented in the survey report or by counting individual rooms on site maps. In some cases sites have been recorded by numerous projects. In these instances the room count estimate is based on the most recent documentation or what was determined to be the most reliable.

Smaller masonry structures (<13 rooms) make up a majority of the masonry sites on Perry Mesa (Kruse-Peeples and Strawhacker 2012). These sites are likely secondary residences near agricultural fields or were fieldhouses, temporary shelter or storage space. In order to avoid double counting population, all sites smaller than 13 rooms were eliminated from the analysis based on population estimates using the *Coalescent Communities* database (Hill et al. 2004). In some cases a recorded “site” included a dozen or more individual 1-3 room structures. While the total room count was greater than 12, there was no single structure this size. These types of sites were excluded from the analysis. An individual structure needed to be greater than 12 rooms to be included in the analysis. Excluding these smaller sites from analysis also prevents potentially earlier, pre-PMT sites from influencing the population estimates. Many of these sites are attributed to the PMT but lack detailed ceramic analysis, or even surface artifacts, to properly designate them to time period. It is suspected that many of these date to the PIII period (Kruse-Peeples and Strawhacker 2012; Wilcox et al. 2001b; Wood in review). Room counts were aggregated for sites containing several individual roomblocks greater than 12 rooms. For example, Pueblo Pato is recorded as having approximately 140 rooms spread across 7 individual roomblocks, the largest of which is estimated to contain between 65-70 rooms.

Thirty-five sites were included in the population estimates (Table 8.1; Figure 8.2). These sites were identified to the PMT and contained more than 12 rooms in a single roomblock. Based on the assumptions of 2 people per room and a 70% occupation rate for sites with 100-249 rooms and 80% occupation rate for sites with 1-99 rooms (after Hill et al. 2004), it is estimated that the PMT population in sites greater than 12 rooms was around 2,711 people. Settlement cluster population estimates range from 120 people (Silver Creek) to around 470 people (Brooklyn, Lousy Canyon, and Perry Tank Canyon).

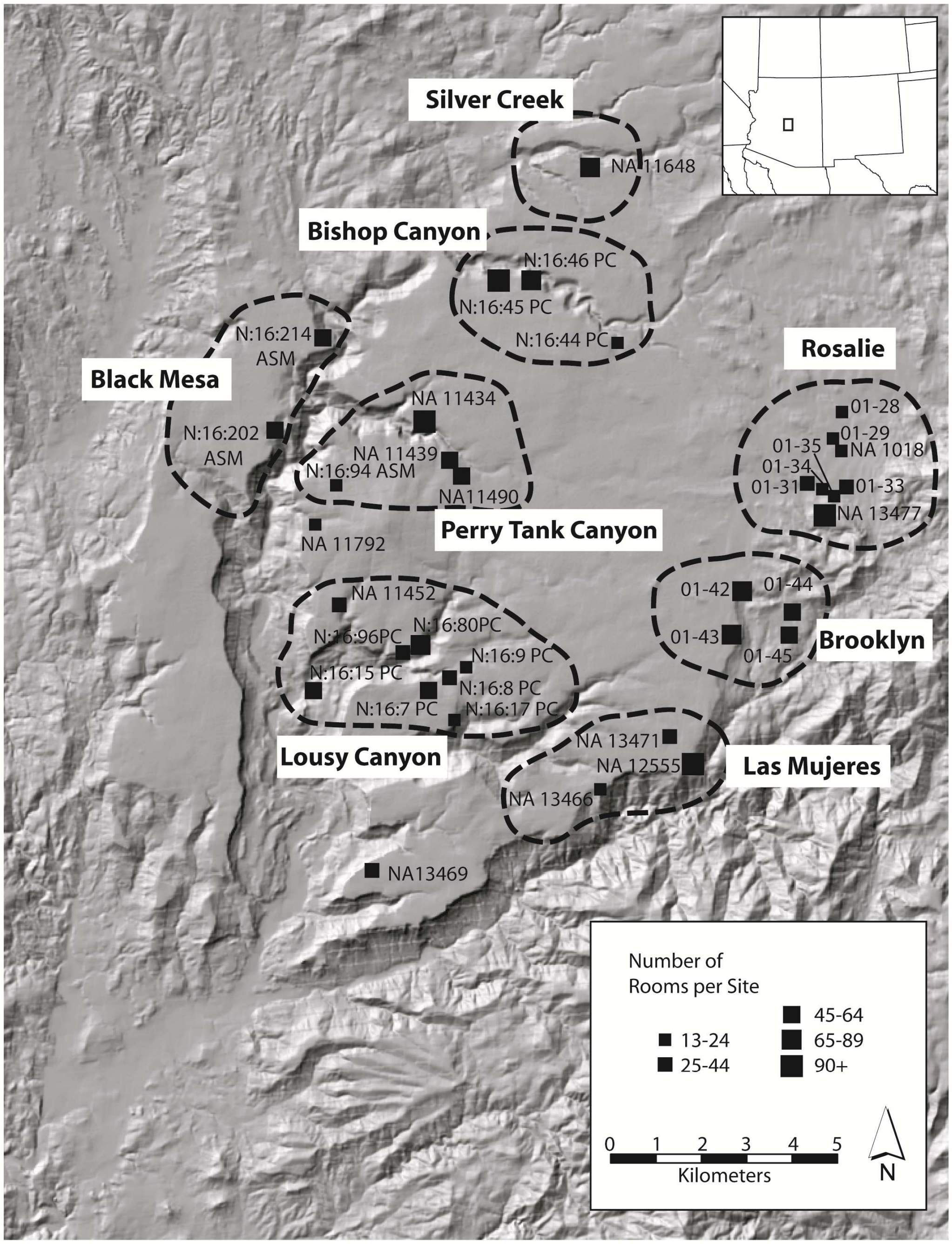


Figure 8.2: Distribution of PMT sites >12 rooms.

Table 8.1. Population estimates for masonry sites (>12 rooms) in the Perry Mesa region.

Settlement Cluster	Site Name, Site Number	Room Count Estimate	Population Estimate	Comment
Bishop Canyon	Baby Canyon Pueblo (N:16:45 PC)	90	144	2 roomblocks
	N:16:46 PC	70	112	2 roomblocks
	N:16:44 PC	14-16	24	
	Cluster Total:	**174-176**	**280**	
Black Mesa	Badger Springs (N:16:214 ASM)	56	90	
	Richinbar Ruin (N:16:202 ASM)	58	93	
	Cluster Total:	**114**	**182**	
Brooklyn	AR 03-12-01-44, NA 7875	40-45	69	
	NA 10070, AR 03-12-01-45	60-90	120	
	Brooklyn (AR 03-12-01-43)	120-140	182	
	NA 9869, AR 03-12-01-42	58	92	2 roomblocks
	Cluster Total:	**278-333**	**463**	
Las Mujeres	Las Mujeres Mound B (NA 13471)	25	40	
	Las Mujeres (NA 12555)	100-125	157	
	NA 13466	20	32	
	Cluster Total:	**145-170**	**229**	
Lousy Canyon	N:16:15, NA 13467	45-50	77	
	N:16:96 PC	30-35	53	
	N:16:80 PC	65-70	109	
	Joe's Site (NA 11452; N:16:292 ASM,)	30	48	
	N:16:7 PC, NA 13467	51	82	
	N:16:17 PC	14-15	22	
	N:16:8 BLM	25-30	44	
	N:16:9 BLM	20	32	
	Cluster Total:	**280-301**	**467**	
Between Lousy and Perry	NA 11792	35-50	69	
Perry Tank Canyon	N:16:94 ASM	20	32	
	Pueblo Pato (NA 11434)	145-152	211	7 roomblocks
	Rattlesnake Mate (NA11490)	48	77	
	Rattlesnake Pueblo (NA 11439)	50	80	
	Cluster Total:	**298-320**	**469**	

Settlement Cluster	Site Name, Site Number	Room Count Estimate	Population Estimate	Comment
Rosalie	Big Rosalie (NA 13477)	100-130	168	2 roomblobks
	AR 03-12-01-31, NA 10065	25-35	48	
	AR 03-12-01-29 NA10019	15-28	35	
	AR 03-12-01-28, NA 10067	20	32	
	AR 03-12-01-33, NA 10020	31	50	
	AR 03-12-01-34	30	48	
	AR 03-12-01-35	15-25	32	
	NA 10018	17	27	
	Cluster Total:	**253-316**	**440**	
Silver Creek	Pueblo La Plata (NA 11648)	70-80	120	
	Cluster Total:	**70-80**	**120**	
South of Lousy Canyon	NA 13469	30-45	61	
REGIONAL TOTAL		**1642-1855**	**2711**	

Previous calculations of PMT population range between 2,801 to 3,502 people based on 1,751 rooms (Wilcox et al. 2001a). This estimate assumes that 10 m^2 is necessary per person; room sizes in the study area are between 16 to 20 m^2 (Wilcox et al. 2001a:160). Despite different assumptions and additional sites, the total Perry Mesa population estimates are similar. Most of the sites recorded in the last decade have been small sites with little impact on population estimates. At this point it is unlikely that many larger sites (>12 rooms) have yet to be located and recorded. Therefore it is unlikely that the overall population estimate as undertaken here will be altered. What is likely, however, is that future research will be able to designate sites, or portions of sites, to early or late phases of the PMT period.

PMT period sites are arranged in evenly spaced settlement clusters along the perimeter of the mesa (Figure 8.2). Each cluster contains at least 1 residential pueblo greater than 55 rooms and most contain numerous sites larger than 12 rooms (Table 8.1). Determining the relationships among sites within clusters is outside the scope of this analysis but there is clearly potential to determine 1) if all sites within a cluster were occupied simultaneously, and 2) the relationships among sites in a cluster. However, given the spatial proximity of individual roomblocks, it is likely that settlement clusters function as a type of dispersed community (Kruse-Peeples and Strawhacker 2012) and likely coordinated access to agricultural land within a cluster. There are also two sites greater than 12 rooms that cannot be assigned to a settlement cluster based on spatial distance, NA 11792, between Perry and Lousy Canyons, and NA 13449 located above the confluence of the Agua Fria River and Squaw Creek. Population estimates were calculated for each individual site as well as for the cluster as a whole (Table 8.1).

Land Use Estimate

Estimates of the amount of agricultural land required per person or household using traditional techniques and cultigens are highly variable and depend upon historic data that may not be directly analogous to prehistoric conditions. Using historic yield estimates to understand prehistoric yields can be misleading due to the evolution of maize over time. Ancient maize ears increased in size over time and it is likely that individual plants produced fewer ears leading to lower yields. Similarly, the reliance on cultigens, particularly maize, increased over time and varied geographically.

Nonetheless, historic yield data and ethnographic information on cultivation techniques can serve as a proxy for prehistoric conditions. A recent synthesis of historically recorded Native American fields in the Southwest documents maize yields ranging from 48 kg/acre to 951 kg/acre (120 kg/ha to 2,350 kg/ha; Mabry 2005:131,

Figure 5.8). The lowest yielding field types were rainfed fields with the highest yielding fields receiving more abundant water from irrigation or recessional floodwaters. Runoff farmed fields yields were highly variable but generally yielded maize quantities between irrigated and rainfed fields. Historic yields of other cultigens, specifically beans, have also been found to be higher in irrigated contexts than runoff field strategies (Arbolino 2001). This suggests that yield variation is related to water-related cultivation practices. Unfortunately much of the historic yield data are from a single year snapshot and do not provide details on how climate trends and declining soil fertility influence yields.

The contexts with historic yield data that are most similar to Perry Mesa are Hopi and Zuni, where similar runoff cultivation techniques were practiced. When he was at Hopi in the late 1800s, Stephen (1936) estimated that a fully planted acre produced around 10-12 bushels (254-305 kg/ac). He estimated that a single person consumed about 12 bushels a year and an additional 18 bushels were needed for seed, long-term storage, and trade. One bushel of corn is 25.4 kg (56 lbs). Stephen was quick to mention that the specific yield depended upon the soil and the seasonal rainfall, with yields approaching 15 bushels per acre of good land with good precipitation. Stephen's yield estimates are similar to contemporary Zuni where in 1998 an average of 12.2 bushels/acre was produced in fields receiving runoff (Muenchrath et al. 2002).

Using Stephen's (1936) yield estimates, Bradfield (1971) concluded that 2.5 acres of land met the subsistence, storage, barter, and seed needs for each person on the Hopi mesas where rainfed and runoff farming were practiced. His estimates includes 1.5 acres for subsistence corn production, 0.5 acre for surplus corn production for trade, and an additional 0.5 acre for production of other vegetables such as beans, melons, and squash.

Bradfield's 2.5 acre per person estimate has been used in calculations of prehistoric land requirements for runoff or floodwater strategies (e.g., Hill 1998).

In this study, I also assumed that 2.5 acres of agricultural land was necessary to be in production per year for every person. This estimate is assumed to meet the annual requirement of subsistence, storage, barter, and seed. This per person estimate however does not take into account the amount of land necessary to be in fallow rotation to ensure maintenance of soil fertility for long-term cultivation. In order to estimate the total number of acres required per person, cultivation plus fallow requirements, the fallow period estimates determined in Chapter 7 are used. To review, simulation model results indicated that if land were cultivated for 5 years it would take 6, 8, and 10 years of fallow for nitrogen levels to return to precultivation levels during wet, average, and dry climatic regimes, respectively. Fallow periods would need to be longer during dry and shorter during wet regimes due to the frequency of high intensity runoff-producing storms in the latter situation. Therefore, more total amounts of land are estimated to be necessary for every person during dry periods compared to wet. Specifically it is estimated that 5.5, 6.5, and 7.5 acres of land are necessary per person during wet, average, and dry climate regimes. The estimated amount of land *under cultivation* is assumed to be the same, 2.5 acres per person during all climate periods.

Climatic Reconstructions

Scott Ingram (2009; 2012; 2013) has reconstructed climate for central Arizona, including the Perry Mesa region. Because trees appropriate for paleoclimatic reconstructions are not available on Perry Mesa, he correlated modern meteorological stations near Perry Mesa with precipitation reconstructions for the San Francisco Peaks

Table 8.2. Estimated amount of land needed during different climate regimes under a 5 year cultivation cycle.

Climatic Regime	Acres in Cultivation	Acres in Fallow	Total # of Acres Required per Person
Wet	2.5	3.0	5.5
Average	2.5	4.0	6.5
Dry	2.5	5.0	7.5

from Salazer (2000; Salazer and Kipfmueller 2005). Ingram evaluated the statistical strength of the correlation between the modern precipitation records from the Cordes meteorological station, located 13 km northwest of Perry Mesa, and stations in the San Francisco Peaks area. Finding this correlation to be strong, Ingram was then able to apply the San Francisco Peaks reconstruction to Perry Mesa with confidence. Similar methodology was used to reconstruct temperature.

The reconstruction provides an estimated annual precipitation value in inches and Ingram identified wet and dry periods based on deviations from the overall mean annual precipitation for the series (Figure 8.3). Year-to-year variation was smoothed by applying a nine-interval moving average based on methods used by other climate studies. This

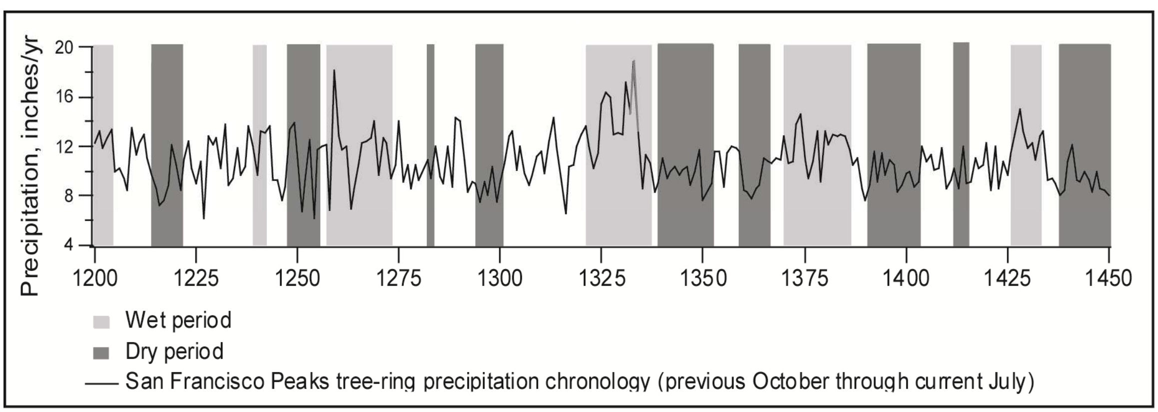


Figure 8.3. Estimated annual precipitation levels and wet and dry periods. Data from Ingram 2009, 2012.

smoothing effect ignores anomalous years within a broader pattern of precipitation. For example, a single wet year during a dry period would not end the dry period (Ingram 2012: 245). Dry periods are identified as nine-year intervals in the first quartile (twenty-fifth percentile) and wet as nine-year intervals in the third quartile (seventy-fifth percentile; Ingram 2009, 2012). Average climatic regimes are interpreted to be all other intervals, those in the second quartile (fiftieth percentile).

Here I focus on the period from A.D. 1200 through A.D. 1450, which includes the PMT period and years immediately preceding and following the regional occupation to establish the context of late 1200s population growth. During this 250-year period there are 62 years identified as wet, 69 identified as dry, and 119 identified as average.

Evaluation

In order to evaluate if there was enough land available to support the estimated land amounts per person (Table 8.2), the potentially arable land and population estimates were compared with the estimated land requirements. This evaluation considered two spatial scales. The first considers the amount of arable land within 2-km catchments around each settlement within a settlement cluster. The second considers population and arable land estimates for the entire Perry Mesa region. Reconstructed climatic data from Ingram (2012) were used to determine which points in the occupation history may have experienced arable land excesses and land shortages.

Arable Land Distribution for each Settlement Cluster

The amount of potentially arable land around each settlement cluster was calculated based on a single 2-km cost equivalent buffer around all sites greater than 12 rooms within the cluster (Figure 8.4; Table 8.3). A 2-km cost equivalent radius was selected

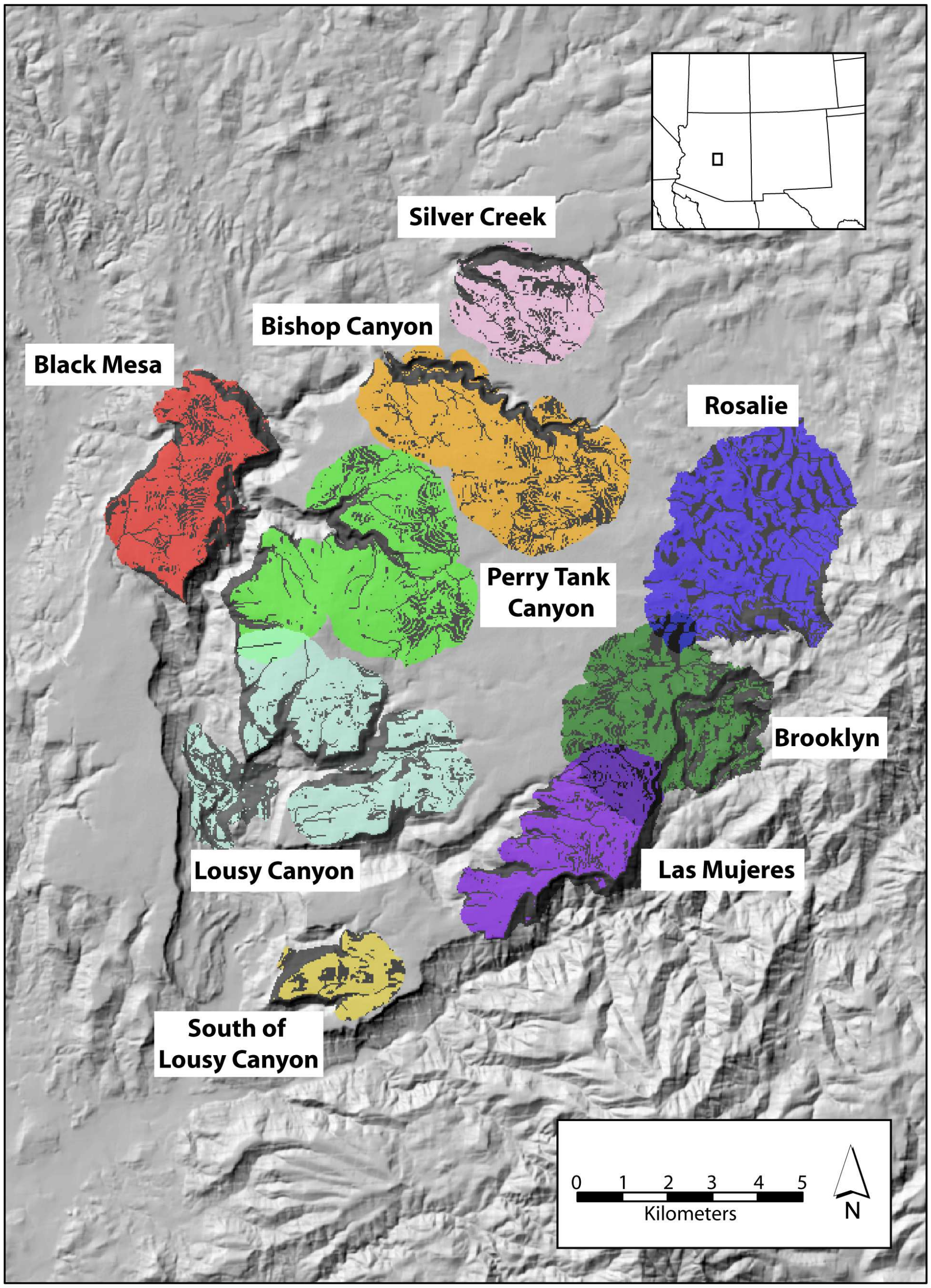


Figure 8.4. Perry Mesa settlement clusters and the distribution of potentially arable land within 2 km cost equivalent catchments.

as a reasonable estimate for the distance people will travel from their residence to tend agricultural land. Cross-cultural ethnographic studies also support the rationale that a 2-km radius around a settlement is typically the area farmers regularly use for the most intensive cultivation (Chisholm 1970; Stone 1996). Varien (1999:153-154) similarly defines a 2-km cost equivalent radius around settlements as the most intensively used area for cultivation in his analysis of community interaction in the Mesa Verde region. He based this estimate on archaeological interpretations from the Dolores Archaeological Program that found the maximum one-way distance between habitations and agricultural fields was an average of 1.7 km (Kohler 1992). Moreover, the distribution of archaeological sites on Perry Mesa supports the use of a 2-km radius as a reasonable estimate for the maximum distance to fields. A majority of the large residential sites are typically separated by 4.5 to 5 km and a 2-km radius around each creates only a small catchment overlap between the Perry Tank and Lousy Canyon clusters and the Brooklyn cluster with both the Las Mujeres and Rosalie clusters (Figure 8.4).

Cost equivalent catchments are calculated taking into account the effort, or cost, of traversing variable terrain. For the most part the terrain of the study area is characterized by gentle hills, and is relatively easy to traverse. However, the flat mesa is cut by deep canyons. Calculation of a cost equivalent distance takes into account that traveling across deep canyons would consume more energy than walking across level terrain. Using the cost equivalent catchment area is important because the ease of traveling to an agricultural field would influence where it would be located. For example, a standard, straight line 2 km catchment around Richinbar Ruin would include areas

Table 8.3. Population estimates for masonry sites (>12 rooms) and amount of potentially arable land.

Settlement Cluster	Number of Sites (>12 rooms) in Cluster	Acres of Potentially Arable Land	Proportion of Catchment Potentially Arable
Baby Canyon	3	1159	70
Black Mesa	2	1533	63
Brooklyn	4	1945	61
Las Mujeres	3	1637	68
Lousy Canyon	8	2553	61
Perry Tank Canyon	4	3071	74
Rosalie	8	2653	69
Silver Creek	1	1013	66
South of Lousy Canyon	1	526	59

across the deep Agua Fria canyon. It is unlikely fields frequently farmed by the residents of Richinbar Ruin would be located on the other side of a 700 m deep canyon.

The cost equivalent catchment areas were calculated with ArcGIS software using methodology developed and explained in detail by Hill (1998, 2006; Herhahn and Hill 1998) and also used in a similar study by Varien (1999). The 2-km cost distance is equivalent to the energy required to traverse 2-km on a landscape with a 2 degree incline, any cells that had a value above this were removed from the catchment. The 2-km catchments for each site within a cluster were combined to create a single catchment for the entire cluster. The size of each settlement catchment varies, depending upon the number of individual roomblocks, their spatial arrangement, and proximity to steep topographic features. The catchments with the most potentially arable land, Perry Tank, Lousy Canyon, Rosalie, and Brooklyn, are also the settlement clusters with the most roomblocks and highest population estimates. Despite the catchment size, all have similar proportions of potentially arable land, ranging from 59% to 74%, with an average of 65% (Table 8.3).

In order to determine if there was enough arable land within each settlement cluster, the amount of land need during dry, average, and wet climate regimes was determined and compared to the number of potentially arable acres in each cluster. The result was a determination of the likely surplus or deficit of arable land per cluster catchment during different climatic regimes (Table 8.4).

The amount of arable land needed for active cultivation was previously estimated to be 2.5 acres per person per year. Considering this estimate, all settlement clusters have a sizeable surplus of arable land[1]. Using this land use estimate, however, does not fully appreciate the need for fallow and nutrient cycling which was previously demonstrated to be dependent upon climatic regimes due to the number of probably runoff replenishment events. Using land use requirements that consider long-term nutrient cycling provides a richer understanding of the agricultural landscape.

During wet regimes, when it is estimated that 5.5 acres are required per person per year for active cultivation and fallow, the Baby Canyon, Brooklyn, and Lousy Canyon Clusters experience an arable land deficit. All other clusters are estimated to have had a sizable surplus within their respective catchments during wet regimes. The Lousy Canyon deficit is estimated to be less than 15 acres and likely had little impact on these populations. Residents at the Baby Canyon sites on the south side of the canyon could have easily expanded their farmland into areas on the north side of the canyon with a little extra effort and the use of temporary structures. The 2 km cost equivalent catchment calculated for the Baby Canyon area does not include much of the land north of the

Table 8.4. Amounts of arable land surpluses or deficits (shaded) estimated for each settlement cluster and climate regime.

Settlement Cluster	Population Estimate	Acres of Potentially Arable Land			Climate Regime					
			2.5 acres per person		Wet 5.5 acres per person		Average 6.5 acres per person		Dry 7.5 acres per person	
			Need	Surplus or Deficit (-)	Need	Surplus or Deficit (-)	Need	Surplus or Deficit (-)	Need	Surplus or Deficit (-)
Baby Canyon	280	1159	700	459	1540	-381	1820	-661	2100	-941
Black Mesa	182	1533	455	1078	1001	532	1183	350	1365	168
Brooklyn	463	1945	1157.5	787.5	2546.5	-601.5	309.5	-1065.5	3472.5	-1528.5
Las Mujeres	229	1637	572.5	1064.5	1259.5	377.5	1488.5	148.5	1717.5	-80.5
Lousy Canyon	467	2553	1167.5	1385.5	2568.5	-14.5	3035.5	-481.5	3502.5	-945.5
Perry Tank Canyon	469	3071	1172.5	1898.5	2579.5	491.5	3048.5	22.5	3517.5	-446.5
Rosalie	440	2653	1100	1553	2420	233	2860	-207	3300	-647
Silver Creek	120	1013	300	713	660	353	780	233	900	113
South of Lousy Canyon	61	526	152.5	373.5	335.5	190.5	396.5	129.5	457.5	68.5
Total for cluster catchments	2711	16090	6777.5	9312.5	14910.5	1179.5	17621.5	-1531.5	20332.5	-4242.5
Total for entire Perry Mesa study area	2711	30533	6777.5	23755.5	14910.5	15622.5	17621.5	12911.5	20332.5	10200.5

canyon, including the entire northern half of the Bull Tank Agricultural Field, due to a higher travel costs associated with traversing the canyon. Expansion into this area may be why the north side of Baby Canyon has a high density of terraced agricultural land (Fish et al. 1975; Kruse-Peeples et al. 2009). Similarly Lousy Canyon residents could have expanded to the south. Relatively little is known about the sites in the Lousy Canyon area which were mainly investigated during the CAEP project of the 1970s (Gumerman et al. 1975, Spoerl and Gumerman 1984). No single site is estimated to be larger than 70 rooms but there is a density of 8 roomblocks with over 13 rooms each. Perhaps more of these individual rooms or roomblocks are from earlier occupation than the PMT period. Recent resurvey of the transmission line corridor did identify several small sites in the area that were dated to the PIII or early Classic period (North n.d.). It would be worth the effort to create detailed maps and ceramic inventories in the Lousy Canyon cluster.

The residents of the Brooklyn cluster sites would have had a harder time finding potentially arable land within the immediate area due to the close spatial proximity of the Las Mujeres and Rosalie clusters. The 2-km catchment deficit, even during wet periods, is estimated to be 600 acres. These residents would have needed to travel greater distances to find arable land to support soil fertility. It is possible that the population estimates are high for the Brooklyn cluster. Recently Scott Wood (in review) has suggested that a majority of the Preclassic (PIII) period occupation on Perry Mesa was in the Brooklyn and Rosalie portions of Perry Mesa. Fine-grained analysis of ceramics, including excavation data, may help to refine occupation phases and determine that the PMT occupation, and therefore land use requirements, may not have been as high as the estimates presented here.

During average climatic regimes, Rosalie is also estimated to experience arable land deficits in addition to those clusters that likely experienced shortages during wet regimes. Because of the proximity to the Brooklyn cluster, Rosalie is spatially limited to the south but has nearby land for expansion to the north and west of the 2 km catchment. The Lousy Canyon cluster's arable land deficit would have been more dramatic during average climate regimes causing populations to expand beyond the catchment boundaries, likely to the east towards the center of the mesa. As implied with the discussion above, refinement of the chronology would help indicate how the occupation fluctuated throughout the period and if in fact population pressures were present leading to land use expansion beyond the 2-km boundaries.

Las Mujeres and Perry Tank Canyon are added to the group of clusters experiencing potentially arable land deficits during dry climate regimes. Both of these clusters would also be spatially restricted in where residents would have been able to expand beyond the boundaries of the 2-km cost equivalent buffers. Only three clusters, Silver Creek, Black Mesa, and the small cluster South of Lousy Canyon, are estimated to have sufficient arable land under dry conditions. These clusters are also estimated to have the smallest populations.

If populations were at the limit of agricultural land within their vicinity they may have met their agricultural needs through means other than expanding into land outside of their immediate vicinity. For example, establishing strong social connections with populations in a cluster that was not experiencing land stress in their vicinity might have facilitated use of farmland within other cluster catchments or the sharing of agricultural surpluses. I expect that those clusters experiencing land shortages would have more frequent and stronger social connections with clusters that were not experiencing land surpluses than they would with clusters that were also experiencing land shortages. Tracking the presence and strength of social connections between groups of people can be done by tracking the movement of objects, such as plainware or decorated ceramics (Rautman 1993). While the entire region would experience the same climatic conditions, land surpluses and shortages would be felt differently depending upon the local landscape and population density.

Recently Watkins and Kelly (2013) have identified two production sources of plainware ceramics on Perry Mesa, an eastern and a western, based on petrographic evidence. The ceramic samples used to define these sources were collected from the Richinbar, La Plata, Pato, Big Rosalie, and Las Mujeres Pueblos. The East source ceramics are dominated by a schist-and-granite temper, likely found along Squaw Creek directly below the eastern portion of the mesa top. Assemblages from the Las Mujeres and Rosalie clusters are dominated by this source and therefore the schist-and-granite tempered ceramics are inferred to be locally made in the eastern portions of Perry Mesa. The plainware ceramic temper in the western sites is dominated by granitic-dominated sand similar in composition to the sediments found along the Agua Fria River and Silver Creek and therefore inferred to be the local ceramic material in the west, including the Perry Tank Canyon, Black Mesa, and Silver Creek clusters. While not sampled directly in their design, it is likely that the Bishop Canyon and Lousy Canyon clusters are similar the Watkins and Kelly’s western source and the Brooklyn cluster is similar to their eastern ceramic source based on spatial association.

Quantifying the circulated amounts of pottery made within these two sources, they determined that twice as much plain ware pottery was produced in the Perry Mesa East production source than the Perry Mesa West source suggesting a form of ceramic specialization was occurring (Watkins and Kelly 2013). For example, 68 percent of the plain ware found at La Plata, a western site, came from the East source. The residents of Richinbar (35%) and Pueblo Pato (31%) also imported high proportions of their plain ware from the East sources, 35 and 31% respectively. However, sites located within the confines of the eastern source did not have large proportions of western made plain ware ceramics in their assemblages. Big Rosalie (6%) and Las Mujeres (2.5%) only had small proportions of their plain ware pottery produced in the Western production area (Watkins and Kelly 2013:Table 6.3). A significant amount of plain ware pottery was flowing from east to west but very little plain ware pottery was traveling in the opposite direction. What then were the eastern potters receiving in return?

Comparisons of land surpluses and deficits of cluster catchments indicate that the eastern clusters of Las Mujeres, Rosalie, and Brooklyn were experiencing more land deficits than many of the western clusters, especially Silver Creek and Black Mesa. Perhaps eastern cluster pottery producers were receiving food from the western sources in exchange for pottery. It may not have been an exchange of pottery for food but the exchange may also represent close-knit social relationships which would facilitate easterner access to agricultural land in the vicinity of more land-abundant western clusters (Duff 2000; Rautman 1993).

Analysis of ceramic assemblages from all clusters is necessary to further advance our understanding of the inter-cluster social connections on Perry Mesa. Unfortunately due to the homogeneity of naturally available ceramic materials, the production sources identified by Watkins and Kelly (2013) include more than one cluster. Results of this analysis suggest the Bishop Creek cluster experienced land deficits and would also be expected to have similar exchange relationships as the eastern sites do with the western sites. But our current understanding of ceramic production does not allow for separation of ceramics locally produced by inhabitants of Baby Canyon versus Pueblo Pato or La Plata.

the hypotheses about which clusters are expected to have more social connections should be tested more thoroughly to refine the identification of social connections between clusters and among individual sites. However, the dominance of eastern produced plainware ceramics within assemblages of sites in western clusters along with the relatively greater land abundance in the western portions of Perry Mesa suggests that the eastern clusters of Rosalie, Brooklyn, and Las Mujeres specialized in pottery production to offset their agricultural land shortages.

Arable Land Distribution for the Perry Mesa Region

The deficits of potentially arable land would have probably meant the inhabitants of some clusters would have had to seek arable land outside of the 2-km catchment during all climatic periods. Considering the amount of potentially arable land across the entire region, 30,533 acres, there is no land deficit during any climatic regime (Table 8.4; Figure 8.5). Therefore, if residents were able and willing to farm at greater distances from their residential pueblos, there would have sufficient arable land on the Mesa. Archaeological evidence supports that this was in fact what populations did to meet land requirements. While a majority of agricultural terraces and field houses are located within

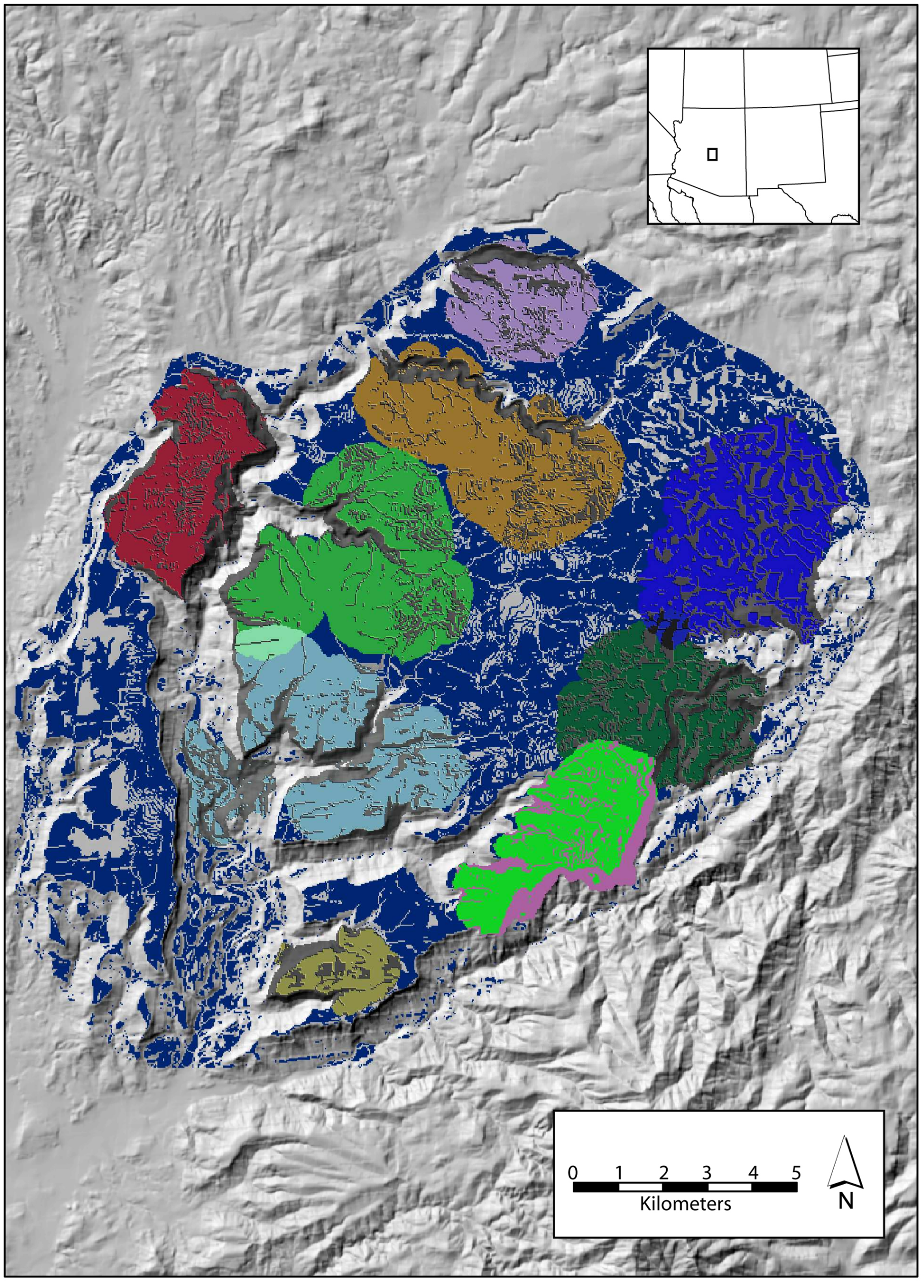


Figure 8.5. Distribution of potentially arable land within the Perry Mesa Region and 2 km cost equivalent catchments for settlement clusters (see Figure 8.4 for labels).

close proximity to the large residential pueblos (Kruse-Peeples et al. 2009), there are agriculturally related sites found across the region. Survey coverage outside of settlement clusters is limited but several east-west transects across the entirety of the Perry Mesa landform completed in the 1990s identified numerous small field houses and small terrace systems (Heuett and Long 1995).

It is also possible that Perry Mesa residents occasionally traveled farther afield outside of the study area considered here to engage in farming activities. Land adjacent to the Agua Fria River, now covered by Black Canyon City, at the southern base of the mesa would have been arable although no existing survey data suggest that it was farmed during the PMT. Arable pockets of land to the east in the Bloody Basin area might have also been used by Perry Mesa farmers. For example, recent survey 14 km east of Perry Mesa has identified a cluster of over 50 small masonry structures within the vicinity of a larger 45-room site dating to the Late Classic (Courtright 2008). While these sites may represent an independent PMT settlement cluster outside of Perry Mesa proper, farmers may have traveled to this area to tend fields.

Evidence for movement of farmers away from their primary residence on Perry Mesa to farm other locals can possibly be tracked through material goods. The disproportionate ceramic exchange documented by Watkins and Kelly (2013) is hypothesized here to be the result of eastern clusters agricultural marginality and the exchange of ceramics for food and access to agricultural land, akin to specialization models proposed by Arnold (1985). However, the patterns observed in the ceramic assemblages may not be indicative of the exchange of goods but rather the movement of people. It is possible that large population segments of eastern communities have moved to the western portions of the landscape, particularly because they offered more agricultural land, and bringing their eastern produced plainware ceramics. They may occupy small fieldhouse structures but might also have lived in larger communities such as Pueblo la Plata or Richinbar. A site may not represent a separate community but rather a summer residence for populations moving to be closer to agricultural fields within the catchment of another cluster. I have previously suggested the possible existence of a dual residence pattern for Perry Mesa (Kruse-Peeples and Strawhacker 2012). A form of residential movement for agricultural purposes on Perry Mesa might have been similar to archaeologically documented patterns of dual residence discussed for the Pajarito Plateau (Preucel 1990) and the Zuni region (Schachner 2012). Additional testing of these ideas is needed and can be addressed by working on fine tuning the chronology of sites occupation on Perry Mesa, investigation of the movement of objects within the landscape of Perry Mesa, and determining the seasonality of residences.

Climatic Context of Arable Land Availability

The potentially arable land surpluses and deficits discussed here relate to the type of climate regime experienced by Perry Mesa farmers. Because of the detailed paleoclimatic reconstructions available (Ingram 2009; 2012; 2013) we can discuss the specific periods when the proposed surplus and deficits were experienced.

There were 3 wet climatic regimes that were long, 16 years duration each, A.D. 1257-1272, A.D. 1321-1336, and A.D. 1370-1385 and a shorter wet period from A.D. 1426-1432. It would have been during the wet periods when pressures on available arable land would be at their lowest. The A.D. 1321-1336 period is particularly exceptional because of its magnitude. It is estimated that precipitation averaged 26 percent above the long-term average for the reconstruction (Ingram 2012: 249). The periodicity of these wet periods is relatively consistent across the period of the PMT occupation. The regularity of wet periods would have been important in quickening recovery of soil fertility and to enhance production. The timing of the first wet period, A.D. 1257-1272, likely influenced the population expansion into the region. Antecedent populations already living on the mesa would have experienced ideal moisture conditions and shorter fallow periods to maintain soil fertility making this region appear attractive for settlement expansion. Recent synthesis provided by Wood (in review) suggests that the pre PMT populations in the area were larger than has been previously understood and that many sites, particularly roomblocks in the eastern portions of Perry Mesa, have evidence of occupation prior to A.D. 1275.

A majority of the late 1200s and the early 1300s experienced average moisture conditions. This likely facilitated continued population expansion and growth into the Perry Mesa region. However, despite being relatively good for moisture and soil fertility recovery, there are deficits in estimated arable land availability for the Baby, Rosalie, Brooklyn, and Lousy Canyon populations. Refinement of chronology to more closely match the paleoclimatic resolution might indicate at which points in time these deficits might have occurred, possibly slowing local site population growth or tracking movement of population within the region that established or allowed growth of other settlement clusters. Overall, however, much of the late 1200s and early 1300s would have had the highest amount of land excess due to the longevity and dominance of wet and average conditions.

Identified dry periods are relatively short compared to wet periods and many average periods. Dry periods range between 6 and 13 years, except for an exceptionally long, 25 year dry period from A.D. 1438 – 1462. The relatively short duration of dry periods means they would have been less dramatic in terms of soil fertility than if they had extended for decades. Also, the shorter duration of many of the dry periods might mean that they were not really observed or impactful to humans. Human response to environmental variability is often a lagged response, requiring several seasons of change before people realize that their conditions are changing. Considering the longer periods of fallow necessary to recover soil fertility during dry periods, however, even these relatively short duration dry periods would have had an impact on production. These dry periods are likely to have been when agricultural infrastructure improvement and expansion into new field areas would have been at their greatest. Given the lag in response some of this infrastructure improvement would extend beyond the measurable dry period into the climatic conditions that would follow a dry period.

It is expected that the 25-year-long dry period would have been the most dramatic and influential to farming populations in the area. This dry period in the mid-1400s was actually the longest dry period that had occurred in at least 868 years and also co-occurred with a long warm period (Ingram 2012). Not only would the demand on arable land have been difficult to meet due to the need for increased fallow for fertility recovery, overall agricultural production would have been severely impacted from the lack of precipitation. This dry period, being of a long duration, would also have been long enough to facilitate a human response. The processes and timing of the depopulation of the Perry Mesa region are currently unclear given current data, but this prolonged dry period could have been what led to complete depopulation of the region. It is also likely that the dry period in the late 1300s and early 1400s began the process of regional abandonment. Refinement of settlement data is needed to further discuss the timing and processes of regional abandonment. As this analysis combined with climatic reconstructions (Ingram 2012) has shown, much of the early and mid-1400s would not have been a favorable period in terms of precipitation and soil fertility.

Conclusions

Using a combination of archaeological evidence, field and laboratory analysis, mathematical modeling, and GIS, I assessed the agroecological system of the Perry Mesa region. I conclude that surface runoff was important, and probably essential in bringing water and nutrients to fields. Terraces improved runoff conditions. However despite the fertility-renewing benefits, fallowing was still necessary to offset the nutrients extracted through farming activities. Thus, more agricultural land was required per person to maintain fertility in this agroecosystem. Climate influenced the frequency and size of runoff-producing events and ultimately, therefore, the rate of nutrient renewal and fallow lengths. Agricultural land deficits did exist for some communities during some climatic regimes but overall there was an abundance of agricultural land in the region.

It is hypothesized that the abundance of agricultural terraces and small field house structures on Perry Mesa is a result of the need to exploit runoff and maintain extensive agricultural land to facilitate fallow cycles. Inter-cluster social connections, as tracked through the circulation of plain ware pottery, are hypothesized to arise from the need for communities in the eastern portion of the mesa to seek out agricultural land and food sharing networks with communities on the western side of the mesa. Although the region likely experienced similar climate conditions, land surpluses and deficits were not homogenous across the region and varied depending upon the local landscape conditions and local population pressures based on population density. It is hypothesized that different clusters had differential access to potentially arable land leading them to expand and contract settlement based on arable land deficits and surpluses.

Future Directions

The implications for this study in understanding Perry Mesa prehistory are hindered by our current chronological resolution. Refining the chronology of Perry Mesa region settlements would help to determine when abandonment of the region occurred, as well as if there is a temporal match between climatic periods and expected patterns of agricultural land expansion, terrace construction, and expansion of existing settlements or establishment of new clusters. Additional excavation and survey data related to later periods of occupation will also be useful in further investigating the processes that led to regional abandonment, not just the timing. While this analysis has shown that the region as a whole had adequate land availability even during dry periods, where this land was located was not ideal for members of specific communities to access it within proximity to their residence. Refinement of chronology will also help with investigations of how Perry Mesa residents responded to the estimated land excesses. In particular, understanding the processes and timing of the depopulation of the Perry Mesa region will help to understand the role of difficult soil fertility renewal conditions during dry periods of the 1400s.

Implications for the Study of Agroecology in the Ancient Southwest

Regional settlement dynamics are frequently discussed in terms of changing climatic patterns. For example, drought conditions have been used to explain large scale migrations across the American Southwest (Benson 2007; Benson and Berry 2009; Dean et al. 1985; Ingram 2009). Climate may be a large pull for people to settle a region (e.g., Perry Mesa in the late A.D. 1200s; Ingram 2013) or a push factor causing people to abandon a region (e.g., Perry Mesa in the early A.D. 1400s; Ingram 2013). However, climate is only one part of the agroecosystem. In this study I have attempted to understand agricultural capacity by integrating factors related to climate *and* soil fertility. Determining how long fields can be farmed, fallow lengths and strategies that maintain soil fertility helps us go beyond climate to understand land use and agricultural production challenges. Flexible local access to agricultural land and maximization of nutrient renewal of runoff with terraces was a critical strategy for maintaining agricultural production in the Perry Mesa region and beyond.

Using a similar approach to the one here might be useful in understanding land use histories in other environmentally similar regions of the Southwest where runoff farming was practiced, including central and northeastern Arizona, upland mesas in the Mesa Verde and Northern Rio Grande regions, and runoff farming in the upland areas of the Mimbres region. It may be the case that soil fertility was originally higher or renewal rates were much faster in some locations compared to Perry Mesa and fallow periods and investment in infrastructure may not have been necessary. Is this why some locations had large populations but not the widespread distribution of agricultural terraces?

Perhaps the longevity of occupation in some locations can also be explained by the soil fertility conditions. Runoff transported to the valley margins of the long-lived Zuni area, for example, has similar nutrient concentrations but overall more sediment and soil organic matter transported by runoff events (Norton 2007a, 2007b) compared to Perry Mesa. Fallow was and is still necessary within these Zuni locales (Cushing 1920; Sandor et al. 2007) but perhaps these more ideal nutrient renewal conditions, combined with favorable climate, have allowed the Zuni River Valley to be occupied for considerably longer than the upland region of Perry Mesa. There is potential to integrate the runoff renewal data generated for the Zuni region into a model similar to the one presented here.

Implications for the Study of Agroecology for Contemporary Arid Agriculture

Many contemporary smallholder agriculturalists are located in areas comparable to Perry Mesa where similar soil fertility recovery strategies may be necessary. The study of agroecology in these contemporary situations should similarly consider fertility in addition to considerations of climate and fluctuations in precipitation.

Contemporary smallholder agriculturalists typically do not have the same land surpluses discussed in this case. Perry Mesa inhabitants had the ability to expand to other areas of the region when fields lied fallow for recovery or even eventually migrating out of the region. This is not case with modern agriculturalists where even fallow is not always an option due to land shortages or the risk of starvation. In the Sahael region of Africa, for example, land shortages have shortened fallow periods from a traditional average of 15 years to just 2-5 years and is severely impacting fertility and yields (Graef and Haigis 2001). Education and aid in this region are now focusing on alternative soil fertility improvements such as harnessing runoff as a source of nutrients and investment in the infrastructure and labor needed to maintain these systems.

The assessment of the Perry Mesa agroecosystem has shown that even when there is land access to migrate to new fields, soil fertility maintenance strategies including infrastructure improvements through terracing, the practice of fallow, and use of labor to actively manage soil fertility are essential. This assessment provided here argues that there is a need to invest in these strategies as a way to maintain agricultural production in the ancient and contemporary world. Many, such as terracing, have additional water retention benefits. Ancient Southwestern inhabitants could also use settlement migration and field movement as an option if soil fertility was an issue but these options are not always available for contemporary subsistence farmers. Therefore, it is the ancient strategies for renewing soil fertility that are the ultimate application to modern small-scale agriculture.

Chapter 8 Notes

[1] I previously published this result using slightly different methodology (Kruse-Peeples 2013).

REFERENCES

Abbott, David and Katherine Spielmann (editors)
2013 *Alliance and Landscape: 13th and 14th Century Occupation of the Perry Mesa Region of Central Arizona.* University of Utah, Salt Lake.

Adams, E. Charles, and Andrew I. Duff (editors)
2004 *The Protohistoric Pueblo World, A.D. 1275-1600*. University of Arizona Press, Tucson.

Adams, Karen
2004 Anthropogenic Ecology of the North American Southwest. In *People and Plants in Ancient Western North America,* edited by Paul E. Minnis, pp 167-204. Smithsonian Institute, Washington, D.C.

Adams, Karen, Deborah A. Muenchrath, and Dylan M. Schwindt
1999 Moisture Effects on the Morphology of Ears, Cobs and Kernels of a South-western U.S. Maize (*Zea mays* L.) Cultivar, and Implications for the Interpretation of Archaeological Maize. *Journal of Archaeological Science* 26: 483–496.

Ahlstrom, R. V. N. and H. Roberts
1995 *Prehistory of Perry Mesa: The Short-Lived Settlement of a Mesa-Canyon Complex in Central Arizona, ca. A.D. 1200-1450*. Arizona Archaeological Society: Arizona Archaeologist No. 28, Phoenix.

Ahlstrom, Richard V. N., Malcolm Adair, R. Thomas Euler, and Robert C. Euler
1992 Pothunting in Central Arizona: The Perry Mesa Archeological Site Vandalism Study. *Cultural Resources Management Report No. 13.* Forest Service Southwestern Region, U.S. Department of Interior, Bureau of Land Management, Arizona.

Amador, M.F. and S.R. Gliessman.
1990 An ecological approach to reducing external inputs through the use of intercropping. In S.R. Gleissman, *Agroecology: Researching the Ecological Basis for Sustainable Agriculture.* Pp. 146-159. Springer-Verlag: New York.

Anderson, B.T., J.Y. Wang, G. Savucci, S. Gopal, and S. Islam.
2010 Observed trends in summer time precipitation over the Southwestern United Sates. *Journal of Climate* 23:1936-1944.

Arbolino, Risa Diemond
2001 *Agricultural Strategies and Lacor Organization: An Ethnohistoric Approach to the Study of Prehistoric Farming Systems in the Taos Area of Northern New Mexico*. Ph.D. dissertation, Southwern Methodist University, Dallas.

Arnold, Dean
1985 *Ceramic Theory and Cultural Process*. Cambridge University Press, Cambridge.

Baker, J. L. and J. S. Bruder
2002 *Cultural Resource Survey of the Proposed Sunrise Point Rest Area along Interstate-17 North of Black Canyon City, Yavapai County, Arizona*. EcoPlan Associates, Inc., Mesa, Ariz.

Barger, N.N., J.E.Herrick, J. Van Zee, and J. Belnap.
2006 Impacts of biological soil crust disturbance and composition on C and N loss from water erosion. *Biogeochemistry* 77:247-263.

Barrow, Christopher
1990 *Alternative Irrigation: The Promise of Runoff Agriculture.* Earthscan Publications Ltd, London.

Beaglehole, Ernest
1937 *Notes on Hopi Economic Life.* Yale University Publications in Anthropology 15. Yale University Press, New Haven.

Benson, Larry
2011a Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 1: The Southern Colorado Plateau and Rio Grande Regions. *Journal of Archaeological Method and Theory* 18:1–60.

2011b Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 2: The Chaco Halo, Mesa Verde, Pajarito Plateau/Bandelier, and Zuni Archaeological Regions. *Journal of Archaeological Method Theory* 18:61–109.

Benson, Larry, Kenneth Petersen, and John Stein
2007 Anasazi (Pre-Columbian Native-American) Migrations During the Middle 12th and Late 13th Centuries – Were they drought Induced? *Climatic Change* 83: 187–213.

Benson, Larry V. and Michael S. Berry
2009 Climate Change and Cultural Response in the Prehistoric American Southwest. *Kiva* 75(1): 87-117.

Berry, Alison M.
1995 Biological Nitrogen Fixation and Soil Fertility in Southwestern Lands: Implications for Anasazi Agriculture. In *Soil, Water, Biology, and Belief in*

Prehistoric and Traditional Southwestern Agriculture, edited by H. Wolcott Toll, pp. 139-143. New Mexico Archaeological Council, Albuquerque.

Bigas, Harriet, Adeel, Zafar, and Schuster, Brigitte
2009 *Seeing Traditional Technologies in a New Light: Using Traditional Approaches for Water Management in Drylands*. United Nations University International Network on Water, Environment, and Health. Paris, France.

Bilsbarrow, M. H.
1997 *A Cultural Resources Survey of the Interstate-17 Highway Corridor in the Vicinity of the Bumble Bee Traffic Interchange (Mileposts 246.4-250.3 [Northbound] & Mileposts 246.4-251.0 [Southbound]), Four Kilometers (2.5 Mi) North of Black Canyon City, Yavapai County, Arizona. Report No. 97:47*. Archaeological Research Services, Tempe.

Bilsbarrow, M. H., T. L. Cadiente and J. K. Tweedy
1997 *A Cultural Resources Survey of the Interstate-17 Highway Corridor between Sunset Point and Badger Springs Road Interchanges (Mileposts 252.5-255.9 [Southbound]/256.1 [Northbound]), 11 Kilometers (7 Mi) South of Cordes Junction, Yavapai County, Arizona. Report No. 96:88.* Archaeological Research Services, Tempe.

Birkeland, Peter W.
1999 *Soils and geomorphology*, 3rd edition. Oxford University Press, New York.

Bloom, Arnold J.
1997 Nitrogen as a Limiting Factor: Crop Acquisition of Ammonium and Nitrate. In *Ecology and Agriculture*, edited by Louise E. Jackson, pp. 145-164. Academic Press, San Diego.

Bohrer, Vorsila L.
1984 Domesticated and Wild Crops in the CAEP Study Area. In *Prehistoric Cultural Development in Central Arizona: Archaeology of the Upper New River Region*, edited by Patricia M. Spoerl and George J. Gumerman, pp. 183-260. Southern Illinois University Center for Archaeological Investigations Occasional Paper 5, Carbondale.

1991 Recently recognized cultivated and encouraged plants among the Hohokam. *Kiva* 56: 227-235.

Bottomley, P.
1992 Ecology of *Rhizobium* and *Bradyrhizobium*. In *Biological nitrogen fixation*, edited by G. Stacey, R H Burris, H J Evans, pp. 292-347. Chapman and Hall, New York.

Bradfield, M.
1971 *The Changing Pattern of Hopi Agriculture.* Occasional Paper No. 30, Royal Anthropological Institute of Great Britain and Ireland, London.

Brady, Nyle C. and Ray R. Weil
2007 *The Nature and Properties of Soils,* 14th edition. Prentice Hall, New Jersey.

Brown, William L., E.G. Anderson, and Roy Tuchawena, Jr.
1952 Observations on Three Varieties of Hopi Maize. *American Journal of Botany* 39(8):597-609.

Brown, Kenneth L. and Susan Crespin
2009 The Transwestern Phoenix Expansion Project, Data Recovery at 19 Sites on BLM, Arizona State, and Private Land, Pipeline Mileposts 49.7 to 103.7, Maricopa and Yavapai Counties, Arizona Volume 3. TRC Report No. 48936-C-123. Albuquerque, NM.

Burke, I. C., E. T. Elliott, and C. V. Cole
1995 Influence of macroclimate, landscape position, and management on soil organic matter in agroecosystems. *Ecological Applications* 5:124-131.

Buskirk, Winifred
1986 *The Western Apache: Living with the Land before 1950.* University of Oklahoma Press, Norman.

Castetter, Edward F. and Willis H. Bell
1942 *Pima and Papago Indian Agriculture*. University of New Mexico Press, Albuquerque.

Chisholm, Michael
1970 *Rural Settlement and Landuse.* Aldine, Chicago.

Clark, S.P.
1928 Lessons from Southwestern Indian agriculture. College of Agriculture, Experimental Station Bulletin 125. University of Arizona, Tucson.

Claassen, M.M. and R.H. Shaw
1970 Water deficit effects on corn. I. Vegetative components. *Agronomy Journal* 62:649-652.

Climate Assessment for the Southwest (CLIMAS)

2009 October 2009. *Southwest Climate Outlook* 8:10. Accessed 8/30/2009 from, http://www.climas.arizona.edu/files/climas/pdfs/periodicals/SWClimateOutlook_Oct09.pdf

2010a August 2010. *Southwest Climate Outlook* 9:8. Accessed 8/30/2010 from, http://www.climas.arizona.edu/files/climas/pdfs/periodicals/SWClimateOutlook_Aug10.pdf

2010b October 2010. *Southwest Climate Outlook* 9:10. Accessed 10/30/2010 from, http://www.climas.arizona.edu/files/climas/pdfs/periodicals/SWClimateOutlook_Oct10.pdf

2011 October 2011. *Southwest Climate Outlook* 10:10. Accessed 11/15/2011 from, http://www.climas.arizona.edu/files/climas/pdfs/periodicals/SWClimateOutlook_Oct11.pdf

Cobos, Doug and Colin Campbell
2007 *Correcting temperature sensitivity of ECH$_2$O soil moisture sensors*. Decagon Devices Application Note. Accessed on November 25, 2009 from www.decagon.com.

Courtright, J. Scott
2008 *Stone Camp Pueblo Research Project, Project Update, March 2006–April 2008*. Ms. On file, Tonto National Forest Supervisor's Office, Phoenix.

Coulombe, Clement E., Larry P. Wilding, and Joe B. Dixon
1996 Overview of Vertisols: Characteristics and Impacts on Society. *Advances in Agronomy* 57:289-375.

Cummings, Linda Scott and Kathryn Puseman
1995 Appendix A: Pollen and Macrofloral Analysis of Samples from NA 11602. In *Prehistory of Perry Mesa: The Short-Lived Settlement of a Mesa-Canyon Complex in Central Arizona, ca. A.D. 1200-1450*, edited by R.V. N. Ahlstrom and H. Roberts, pp. 85-98. Arizona Archaeological Society: Arizona Archaeologist No. 28, Phoenix.

Cushing, Frank H.
1920 *Zuni breadstuff*. Museum of the American Indian: Heye Foundation, New York.

Dane, J.H. and G.C. Topp eds.
2002 Chapter 2: The solid phase. Methods of soil analysis: Physical methods. Madison, WI. Soil Science Society of America. pp. 201-414.

Dean, Jeffery S., Robery C. Euler, George J. Gummerman, Fred Plog, aRichard H. Gevly, and Thor N. V. Karlstrom

1985 Human Behavior, Demography, and Paleoenvironment on the Colorado Plateaus. *American Antiquity* 50: 537-554.

Dominquez, Steven

2002 Optimal gardening strategies: maximizing the input and retention of water in prehistoric gridded fields in north central New Mexico. *World Archaeology* 34(1): 131–163.

Dominquez, Steven and Kenneth E. Kolm

2005 Beyond Harvesting: A Soil Hydrology Perspective on Traditional Southwestern Agricultural Technology. *American Antiquity* 70(4): 732-765.

Donkin, R. A.

1979 *Agricultural Terracing in the Aboriginal New World.* Viking Fund Publications in Anthropology No. 56. University of Arizona Press, Tucson.

Doolittle, William E.

2000 *Cultivated Landscapes of Native North America.* Oxford University Press: New York.

Doolittle, William E.

1984 Agricultural Change as an Incremental Process. *Annals of the Association of American Geographers* 74(1): 124-137.

Doolittle, William E. And James A. Neely

2004 *The Safford Valley Grids: Prehistoric Cultivation in the Southern Arizona Desert.* Anthropological Papers of the University of Arizona: 70. The University of Arizona Press, Tucson.

Dorshow, Wetherbee Bryan

2012 Modeling agricultural potential in Chaco Canyon during the Bonito phase: a predictive geospatial approach. *Journal of Archaeological Science* (39) 2098-2115.

Douglas, D. L.

1975 Faunal Remains from Archaeological Sites Excavated by the Central Arizona Ecotone Project: 1973-1974 Field Seasons. In *Adaptive Strategies in a Biological and Cultural Transition Zone: The Central Arizona Ecotone Project: An Interim Report*, pp. 96-127. Report to the National Science Foundation, NASA. University Museum Studies No. 6, SIU, Carbondale.

Douglas, Charles L.

1994 *An Archaeological Survey of El Paso Natural Gas Company 1203 Line Repairs, North of Black Canyon City, Yavapai County, Arizona.* Archaeological Consulting Services, Ltd., Tempe.

Drinkwater, Laurie E.
2004 Improving Fertilizer Nitrogen Use Efficiency through an Eco-system Based Approach. In *Agriculture and the Nitrogen Cycle*, edited by Arvin R. Mosier, J Keith Syers, and John R. Freney. Island Press, Washington D.C.

Duff, Andrew I.
2000 Scale, Interaction, and Regional Analysis in late Pueblo Prehistory. In *The Archaeology of Regional Interaction: Religion, Warfare, and Exchange across the American Southwest*, edited by M. Hegmon, pp. 51-71. University of Colorado Press, Boulder.

Euler, Robert C.
1954 Environmental Adaptation at Sia Pueblo. *Human Organization* 12(4):27-30.

Farquharson, A. D., J. R. Meigh, and J. V. Sutcliffe
1992 Regional flood frequency analysis in arid and semi-arid areas. *Journal of Hydrology* 138: 487-501.

Faures, J.M., D.C. Goodrich, D.A. Woolhiser, and S. Sorooshian
1995 Impact of small-scale spatial rainfall variability on runoff modeling. *Journal of Hydrology* 173:309-326.

Fiero, D. C., R. W. Munson, M. T. McClain, S. M. Wilson and A. H. Zier
1980 *The Navajo Project: Archaeological Investigations Page to Phoenix 500KV Southern Transmission Line*. Museum of Northern Arizona MNA Research Paper 11, Flagstaff.

Fish, P. R., P. Moberly and P. J. Pilles, Jr.
1975 Final Report for Phase IIB Archaeological Studies. Ebasco Services Transmission System Study. Manuscript on file, Museum of Northern Arizona, Flagstaff.

Fish, Suzanne K.
1980 Appendix VI: Agricultural Features and their Pollen Record at NA11,504. In *The Navajo Project: Archaeological Investigations Page to Phoenix 500KV Southern Transmission Line*, edited by D. C. Fiero, R. W. Munson, M. T. McClain, S. M. Wilson and A. H. Zier, pp. 261-270. Museum of Northern Arizona MNA Research Paper 11, Flagstaff.

2004 Corn, Crops, and Cultivation in the North American Southwest. In *People and Plants in Prehistoric Western North America*, edited by P.E. Minnis, pp. 115-166. Smithsonian Books, Washington.

Fleming, J. B.
2005 *Hydrologic Characteristics of the Agua Fria National Monument, Central Arizona, Determined from the Reconnaissance Study.* U. S. Geological Survey Scientific Investigation Reports 2004-5163.

Forde, C. Daryll
1931 Hopi Agriculture and Land Ownership. *The Journal of the Royal Anthropological Institute of Great Britain and Ireland* 61: 357-405.

Forde, Cyril Daryll
1948 The Hopi and Yuma: Flood Farmers in the North American Desert. In *Habitat, Economy, and Society: A Geographical Introduction to Ethnology,* 6th ed., edited by Cyril Daryll Forde, pp 220-259. Methuen, London.

Francis, C., G. Lieblin, S. Gliessman, T.A. Breland, N. Creamer, R. Harwood, L. Salomonsson, J. Helenius, D. Rickerl, R. Salvador, M. Wiendehoeft, S. Simmons, P. Allen, M. Altieri, J. Porter, C. Flora, and R. Poincelot
2003 Agroecology: The Ecology of Food Systems. *Sustainable Agriculture* 22:99-118.

Franzluebbers, A.J.
2004 Tillage and residue management affects on soil organic matter. In *Soil Organic Matter in Sustainable Agriculture,* edited by F. Magdoff and R.R. Weil, pp. 227-268. Advances in Agroecology Series. CRC Press, Boca Raton, Florida.

Gardner, Franklin P., Brent R. Pearce, and Roger L. Mitchell.
1985 *Physiology of Crop Plants*. Iowa State University Press, Ames.

Gee, G.W. and D. Or
2002 Particle-size analysis. In *Methods of soil analysis. Part 4. Physical and mineralogical methods,* edited by J.H. Dane and G.C. Clarke, pp. 256-293. SSSA Book Series No. 5. Madison, WI: Soil Science Society of America.

Ghadiri, H. and C.W. Rose
1990a Sorbed Chemical Transport in Overland Flow: I. Enrichment Ratio Variation with Erosion Processes. *Journal of Environment Quality* 20(3):628-633.

1990b Sorbed Chemical Transport in Overland Flow: II. Enrichment Ration Variation with Erosion Processes. *Journal of Environment Quality* 20(3):634-641.

Gifford, Edward W.

1936 Northeastern and Western Yavapai. *University of California publications in American Archaeology and Ethnology* 34(4):247-354.

Gimenez, C., F. Orgaz, and E. Fereres
1997 Productivity in Water-Limited Environments: Dryland Agricultural Systems. In *Ecology in Agriculture*, edited by Louise E. Jackson, pp. 117-137. Academic Press, San Diego.

Gish, Jannifer
1993 Shelltown and the Hind Site: A Pollen Study of Two Settlements, with an Overview of Hohokam Subsistence. In *Shelltown and the Hind Site, A Study of Two Hohokam Craftsman Communities in Southwestern Arizona,* Volume 1, edited by W.S. Marmaduke and R.J. Martynec, pp. 449-562, Northland Research, Flagstaff.

Gliessman, Stephen R.
2007 *Agroecology: The Ecology of Sustainable food Systems.* Taylor & Francis Group. Boca Raton, Florida.

Goodman-Elgar, Melissa
2008 Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces from the Paca Valley, Peru. *Journal of Archaeological Science* 35: 3072-3086.

Goodrich, D. C., C. L. Unkrich, T. O. Keefer, M. H. Nichols, J. J. Stone, L. R. Levick, and R. L. Scott
2008 Event to multidecadal persistence in rainfall and runoff in southeast Arizona. *Water Resources Research* 44, W05S14, doi:10.1029/2007WR006222.

Goodrich, David C., Jean-Marc Faures, David A. Woolhiser, Leonard J. Lane, Soroosh Sorooshian
1995 Measurement and analysis of small-scale convective storm rainfall variability. *Journal of Hydrology* 173: 283-308.

Graef, F. and J. Haigis
2001 Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies. *Journal of Arid Environments* 48: 221–231.

Gumerman, George, J. Hanson, D. Brew, K. Tomoff, and C. Weed
1975 The Hydrology of Prehistoric Farming Systems in a Central Arizona Ecotone. Final Report prepared for Lyndon B. Johnson Space Center. Manuscript on file, Bureau of Land Management, Phoenix Field Office.

Gyssels, G., J. Poesen, E. Bochet, and Y. Li

2005 Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in Physical Geography* 29:189-217.

Hack, John T.
1942 The Changing Physical Environment of the Hopi Indians of Arizona. Papers of the Peabody Museum of American Archaeology and Ethnology 35(1). Harvard University Press, Cambridge, MA.

Hastings, Brian K., David D. Breshears, and M. Smith Freeman
2005 Spatial Variability in Rainfall Erosivity versus Rainfall Depth: Implications for Sediment Yield. *Vadose Zone Journal* 4:500-504.

Haynes, R.J., R.J. Martin, and K.M. Goh
1993 Nitrogen Fixation, accumulation of soil nitrogen and nitrogen balance for some field-grown legume crops. *Field Crops Research* 35: 85-92.

Herhan, Cynthia and Brett Hill
1998 Modeling Agricultural Production Strategies in the Northern Rio Grande Valley, New Mexico. *Human Ecology* 26(3): 468-487).

Heuett, Marylou L., and Paul V. Long, Jr.
1995 *A Cultural Resource Inventory of Fifteen Selected Linear Transects and a 300-Acre Quadrant on Perry Mesa in Southeastern Yavapai County, Arizona*. Cultural & Environmental Systems, Inc., Tucson.

Hill, W.W.
1938 *The Agricultural and Hunting Methods of the Navaho Indians.* Yale University Press, London.

Hill, J. Brett
1998 Ecological Variability and Agricultural Specialization among the Protohistoric Pueblos of Central New Mexico. *Journal of Field Archaeology* 25(3): 275-294.

2006 *Human Ecology in the Wadi al-Hasa: Land Use and Abandonment Through the Holocene*. University of Arizona Press, Tucson.

Hill, J. Brett, Jeffery J. Clark, William H. Doelle and Patrick D. Lyons
2004 Prehistoric Demography in the Southwest: Migration, Coalescence, and Hohokam Population Decline. *American Antiquity* 69(4): 689-716.

Homburg, Jeffery A.
1997 Prehistoric Dryland Agricultural Fields of the Lower Verde Valley. In *Vanishing River: Agricultural, Subsistence, and Environmental Studies*, edited by

Jonathan A. Homburg ad Richard Ciolek-Torrello, pp. 103-126. SRI Press, Tucson, Arizona.

Homburg, Jeffery A.
2000 Anthropogenic influences on American Indian agricultural soils of the Southwestern United States. Ph.D. dissertation, Iowa State University.

Homburg, Jeffery. A., and Jonathan. A. Sandor
1997 An Agronomic Study of Two Classic Period Agricultural Fields in the Horseshoe Basin. In *Vanishing River: Agricultural, Subsistence, and Environmental Studies*, edited by Jonathan A. Homburg and Richard Ciolek-Torrello, pp. 127-147. SRI Press, Tucson, Arizona.

Homburg, Jeffery A. and Jonathan A. Sandor
2011 Anthropogenic effects on soil quality of ancient agricultural systems of the American Southwest. *Catena* 85:144-154.

Homburg, Jeffery. A., Jonathan. A. Sandor, and Dale. R. Lightfoot
2004 Soil Investigations. In *The Safford Valley Grids: Prehistoric Cultivation in the Southern Arizona Desert,* edited by William E. Doolittle and James A. Neely, pp 62-78. Anthropological Papers of the University of Arizona, 70, Tucson.

Homburg, J. A., J.A. Sandor, and J.B. Norton
2005 Anthropogenic influences on Zuni soils. *Geoarchaeology* 20: 661–693.

Hooper, D. U. and L. Johnson
1999 Nitrogen limitation in dryland ecosystems:responses to geographical and temporal variation in precipitation. Biogeochemistry 56:247–293.

Howard, Jerry
2006 Hohokam irrigation communities: A study of internal structure, external relationships and sociopolitical complexity. Ph.D. dissertation, Arizona State University.

Ingram, Scott E.
2009 Conflict and Climate in Prehistoric Arizona. Report on file, School of Human Evolution and Social Change, Arizona State University, Tempe.

2012 The Climatic Context of Population Change on Perry Mesa. In *Prehistoric Cultures of the Perry Mesa Region: Proceedings of the Perry Mesa Symposium,* edited by W.G. Russell and M.J. Hoogendyk, pp. 247-255. The Cultural Resources Committee of Friends of Agua Fria National Monument, Phoenix, AZ.

2013 Climatic, Demographic, and Environmental Influences on Central Arizona Settlement Patterns. In *Alliance and Landscape: 13th and 14th Century Occupation of* *the Perry Mesa Region of Central Arizona.* Edited by David R. Abbott and Katherine A. Spielmann. University of Utah Press, Salt Lake.

Jin, K., Cornelis, W.M., D. Gabriels, M. Baert, H.J. Wu, W. Schiettecatte, D.X. Cai, S. DeNeve, J.R. Jin, R. Hartmann, and G. Hofman
2009 Residue cover and rainfall intensity of effects on runoff soil organic carbon losses. *Catena* 78:81-86.

Johnson, Katie
2005 Agricultural Impacts on Soil Compaction and Sediment Size at Agua Fria National Monument. In *Report of the Spring 2005 Field Season, Legacies on the Landscape: Archaeological and Ecological Research at Agua Fria National Monument*, edited by K.A. Spielmann, pp. 24-35. Report submitted to the Bureau of Land Management and National Park Service.

Kohler, Timothy A.
1992 Field Houses, Villages, and the Tragedy of the Commons in the Early Northern Anasazi Southwest. *American Antiquity* 57(4):617-635.

Kruse, Melissa
2005 Agricultural Site Survey, Spring 2005. In *Report of the Spring 2005 Field Season, Legacies on the Landscape: Archaeological and Ecological Research at Agua Fria National Monument*, edited by K.A. Spielmann, pp. 47-58. Report submitted to the Bureau of Land Management and National Park Service.

2007 The Agricultural Landscape of Perry Mesa: Modeling Residential Site Locations in Relation to Arable Land. *Kiva* 73(1): 85-102.

Kruse-Peeples, Melissa
2013 The Prehistoric Food Supply: Evaluating Self-Sufficiency of Perry Mesa Inhabitants. In *Alliance and Landscape: 13th and 14th Century Occupation of the Perry Mesa Region of Central Arizona.* Edited by David R. Abbott and Katherine A. Spielmann. University of Utah, Salt Lake.

Kruse-Peeples, Melissa, Will G. Russell, Hoski Schaafsma, Colleen Strawhacker, and JoAnn Wallace
2009 Report of the 2007 Archaeological Survey of Northwestern Portions of PerryMesa Within Agua Fria National Monument, Yavapai County, Arizona. Report on file, School of Human Evolution and Social Change, Arizona State University and Bureau of Land Management, Phoenix Office.

Kruse-Peeples, Melissa, Hoski Schaafsma, John Briggs, and Katherine Spielmann
2010 Landscape Legacies of Prehistoric Agricultural Land Use in the Perry Mesa Region, Central Arizona. For *The Archaeology of Anthropogenic Environments,* edited by Rebecca Dean, 122-141. Occasional Paper No. 37,

Center for Archaeological Investigations, Southern Illinois University, Carbondale.

Kruse-Peeples, Melissa and Colleen Strawhacker
2012 Prehistoric Settlement Organization Across Perry Mesa: Considerations of Settlement Size, Distribution and Chronology. In *Prehistoric Cultures of the Perry Mesa Region: Proceedings of the Perry Mesa Symposium,* edited by W.G. Russell and M.J. Hoogendyk, pp. 257-282. The Cultural Resources Committee of Friends of Agua Fria National Monument, Phoenix, AZ.

Kruse-Peeples, Melissa and Jake Lulewicz
2012 Report of Fieldwork in the Vicinity of Bull Tank Agricultural Field 2009-2011. Manuscript on file, Bureau of Land Management, Phoenix Field Office.

Lange, Charles H. and Carroll L. Riley
1966 *The Southwestern Journals of Adolph F. Bandelier, 1880-1882.* University of New Mexico Press, Albuquerque.

Lavee, Hanoch, Jean Poesen and Aaron Yair
1997 Evidence of High Efficiency Water Harvesting by Ancient Farmers in the Negev Desert, Israel. *Journal of Arid Environments* 35:341-348.

Lister, D.
2007 *Land degradation and nutrient dynamics within the Jornada Basin, New Mexico.* Ph.D. dissertation, University of Bristol.

Ludwig, J. A.
1987 Primary productivity in arid lands: myths and realities. *Journal of Arid Environments* 13:1-7.

Magistro, John and Carla Roncoli
2000 Anthropological perspectives and policy implications of climate change research. *Climate Research* 19(2): 91-96.

Maingi, John M., Chris A. Shisanya, Nkanata M. Gitonga, and Berthold Hornetz
2001 Nitrogen fixation by common bean (*Pahseolus vulgaris* L.) in pure and mixed stands in semi-arid south-east Kenya. *European Journal of Agronomy,* 14:1-12.

Mallam Issa, O., Y. Le Bissonnais, O. Planchon, David Favis-Mortlock, Norbert Silvera, and John Wainwright
2006 Soil detachment and transport on field and laboratory scale interill areas. *Earth Surface Process and Landforms* 31:929-939.

Manolescu, Kathleen

1995 Hopi Corn Production. A Report on Research Conducted for the Bureau of Indian Affairs, Phoenix Area Office. MS on file at Hopi Cultural Preservation Office, Kykotsmovi, Arizona.

Massey, H.F. and M.L. Jackson
1952 Selective erosion of soil fertility constituents. *Proceedings from Soil Science Society of America* 16:353-356.

Maxwell, T. and K. Anschuetz
1992 The Southwestern Ethnographic Record and Prehistoric Agricultural Diversity. In *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica,* edited by Thomas W. Killion, pp 35-68. The University of Alabama Press, Tuscaloosa.

McAuliffe, Joseph R.
1994 Landscape Evolution, Soil Formation, and Ecological Patterns and Processes in Sonoran Desert Bajadas. *Ecological Monographs* 64(2): 111-148.

Mermut, A.R., G.S. Daso, and G.N. Dowuona
1996 Soil morphology. p. 89–114. In *Vertisols and technologies for their management,* edited by N. Ahmad and A. Mermut, pp. 89-114. Developments in Soil Science 24. Elsevier, Amsterdam, The Netherlands.

Moorhead, Daryl L., James F. Reynolds, and Walter G. Whitford
1985 A conceptual model for primary productivity, decomposition and nitrogen cycling in the Chihuahuan cresosotebush desert. *Tree Physiology* 2: 215-222.

Muenchrath, Deborah A., Maya Kuratomi, Jonathan A. Sandor and Jeffery A. Homburg
2002 Observational study of maize production systems of Zuni framers in semi arid New Mexico. *Journal of Ethnobiology* 22(1): 1-33.

Muenchrath, Deborah A. and Ricardo J. Salvador
1995 Maize Productivity and Agroecology: Effects of Environment and Agricultural Practices on the Biology of Maize. In *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture*, edited by H. Wolcott Toll, pp. 303-333. New Mexico Archaeological Council, Albuquerque.

Nabhan, Gary P.
1983 Papago Field: Arid Lands Ehtnobotany and Agricultural Ecology. Ph.D. dissertation, Department of Arid Lands Resource Sciences, University of Arizona, Tucson.

1984 Soil fertility renewal and water harvesting in Sonoran Desert agriculture: the Papago example. *Arid Lands Newsletter* 20: 20-28. Office of Arid Lands Studies, University of Arizona, Tucson.

1986 Ak chin 'arroyo mouth' and the environmental setting of the Papago Indian fields in the Sonoran Desert. *Applied Geography* 6: 61-75.

Nachabe, M.H., L.R. Ahuja, and Renee Rokicki
2003 Soils, Field Capacity of Water. In *Encyclopedia or Water Science*, edited by Bobby Alton Stewart and Terry A. Howell, pp 915-922. Marcel Dekker, Inc. New York.

Nakase, Danna
2012 Eolian Deposition and Soil Fertility in a Prehistoric Agricultural Complex in Central Arizona. M.A. Thesis, Arizona State University.

Niemeijer, D.
1998 Soil Nutrient Harvesting in Indigenous Teras Water Harvesting in Eastern Sudan. *Land Degradation and Development.* 9:323-330.

North, Chris D.
2002 Farmers of Central Arizona's Mesa-Canyon Complex: Archaeology Within and Adjacent to the Agua Fria National Monument. SWCA Cultural Resource Report No. 02-339. Phoenix, AZ.

North, Chris D.
n.d. A Cultural Resources Survey of 5,130 Acres of State and Federal Land for The Arizona Public Service 500-2 Transmission Line between the Westwing Substation and the Navajo Indian Reservation Boundary, Maricopa, Yavapai, and Coconino Counties, Arizona. LSD Technical Report No. 075107 (500-2c). Manuscript on file Logan Simpson Design, Tempe, Arizona.

Norton, Jay B., Roman R. Pawluk and Jonathan A. Sandor
1998 Observation and experience linking science and indigenous knowledge at Zuni, New Mexico. *Journal of Arid Environments* 39: 331–340.

Norton, Jay B., J. A. Sandor, and C. S. White.
2003 Hillslope Soils and Organic Matter Dynamics within a Native American Agroecosystem on the Colorado Plateau. *Soil Science Society of America Journal* 67:225–234.

Norton, Jay B., J.A. Sandor, C.S. White
2007a Runoff and Sediments from Hillslope Soils within a Native American Agroecosystem. *Soil Science Society of America Journal* 71(2):476-483.

2007b Organic matter transformations through arroyos and alluvial fan soils within a Native American agroecosystem. *Soil Science Society of America Journal* 71(3):829–835.

Norton, Jay B., Jonathan A. Sandor, Roman R. Pawluk
2001 Farmer Scientist Collaboration for Research and Agricultural Development on the Zuni Indian Reservation, New Mexico, USA. *Sustainability of Agricultural Systems in Transition*. ASA Special Publication no. 64.

Olson, R. A. and D. H. Sander
1988 Corn Production. In *Corn and Corn Improvement* (3rd Ed., ASA Monograph No. 18), edited by G.F. Sprague and J.W. Dudley, pp. 639-686. American Society of Agronomy.

Palis, R.G., H. Ghandiri, C.W. Rose, and P.G. Saffigna
1997 Soil erosion and nutrient loss: Changes in enrichment ratio of total nitrogen and organic carbon under rainfall detachment and entrainment. *Australian Journal of Soil Research* 35:891-905.

Parsons, A.J., A.D. Abrahams, and S. Luk
1991 Size characteristics of sediment in interill overland flow on a semi-arid hillslope, Southern Arizona. *Earth Surface Processes and Landforms* 16:143-152.

Parsons, Anthony J., Richard E. Vrazier, John Wainwright, and D. Mark Powell
2006 Scale Relationships in Hillslope Runoff and Erosion. *Earth Surface Processes and Landforms* 31: 1384-1393.

Parton, W. J., D.S. Schimel, C.V. Cole, and D.S. Ojima
1987 Analysis of Factors Controlling Soil Organic-Matter Levels in Great-Plains Grasslands. *Soil Science Society of America Journal* 51: 1173–1179.

Perret, S. and M. Dorel
1999 Relationships between land use, fertility and Andisol behaviours: examples from volcanic islands. *Soil Use and Management* 15:144-149.

Peoples, M.B., D.F. Herridge, and J.K. Ladha
1995 Biological Nitrogen Fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant and Soil* 174: 3-28.

Pilles, Peter J., Jr.
1996 The Pueblo III Period along the Mogollon Rim: The Honanki, Elden, and Turkey Hill Phases of the Sinagua. In *The Prehistoric Pueblo World, A.D. 1150-1350,* edited by Michael A. Adler. University of Arizona Press, Tucson.

Pleasant, Jane MT.
2006 The Science behind the Three Sisters Mound System: An Agronomic Assessment of an Indigenous Agricultural System in the Northeast. In *Histories of Maize.* edited by John E Staller, Robert H. Tykot, and Bruce F. Benz. Academic Press.

Poesen, J. and H. Lavee
1994 Rock fragments in top soils: significance and processes. *Catena* 23: 1–28.

Preucel, R. W.
1990 *Seasonal Circulation and Dual Residence in the Pueblo Southwest: A Prehistoric Example from the Pajarito Plateau, New Mexico.* Garland Publishing, Inc., New York.

Prevost, D.J., R.J. Ahrens, and D.M. Kriz
1984 Traditional Hopi Agricultural Methods. *Journal of Soil and Water Conservation* 39: 170-171.

Ramos, M.C. and J.A. Martinez-Casasnovas
2006 Nutrient losses by runoff in vineyards of the Mediterranean Alt Penedes region (NE Spain). *Agriculture Ecosystems and Environment* 113: 356–363.

Rankin, Adrianne G.
1989 Agricultural Features. In *Settlement, Subsistence, and Specialization in the Northern Periphery: The Waddell Project,* Vol. 2, edited by Margerie Green, pp. 69-175. Cultural Resources Report 65. Archaeological Consulting Services, Tempe, Arizona.

Rautman, Alsion
1993 Resource Variability, Risk, and the Structure of Social Networks: An Example from the Prehistoric Southwest. *American Antiquity* 58:403-424.

Redman, Charles L.
1993 *People of the Tonto Rim: Archaeological Discovery in Arizona*. Smithsonian Institution Press, Washington. (Natural History Book Club selection

Reynolds, R., J. Belnap, M. Reheis, P. Lamothe, and F. Luiszer
2001 Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. *Proceedings of the National Academy of Science* 98:7123-7127.

Robertson, Philip G.
1997 Nitrogen Use Efficiency in Row-Crop Agriculture: Crop Nitrogen Use and Soil Nitrogen Loss. In *Ecology in Agriculture,* edited by Louise E. Jackson, pp. 347-362. Academic Press, San Diego.

Ruhe, R. V., and P. H. Walker
1968 Hillslope models and soil formation. I. Open systems. In *Transactions of the Ninth International Congress of Soil Science, Adelaide, Australia*, pp. 551-560. Angus and Robertson, London, UK.

Salazer, Matthew W.
2000 *Dendroclimatology in the San Francisco Peaks Region of Northern Arizona, USA.* Ph.D. Dissertation, University of Arizona.

Salzer, Matthew W., and Kurt F. Kipfmueller
2005 Reconstructed Temperature and Precipitation on a Millennial Timescale from Tree-Rings in the Southern Colorado Plateau, USA. *Climatic Change* 70(3):465-487.

Sandor, Jonathan A.
1995 Searching Soil for Clues about Southwest Prehistoric Agriculture. In *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture*, edited by H. Wolcott Toll, pp. 119-137. New Mexico Archaeological Council, Albuquerque.

2006 Ancient Agricultural Terraces and Soils. In *Footprints in the Soil: People and Ideas in Soil History,* edited by Benno P. Warkentin, pp 505-534. Elsevier, Amsterdam.

Sandor, Jonathan and N. S. Eash
1991 Significance of Ancient Agricultural Soils for Long-Term Agronomic Studies and Sustainable Agriculture Research. *Agronomy Journal* 93: 29-37.

Sandor, J. A., P.L. Gersper and J.W. Hawley
1986 Soils at Prehistoric agricultural terracing sites in New Mexico 1: organic matter and bulk density changes. *Soil Science Society of America Journal* 50: 173–177.

1990 Prehistoric Agricultural Terraces and Soils in the Mimbres area, New Mexico. *World Archaeology* 22:70-86.

Sandor, J. A., Norton, J. B., Pawluk, R. R., Homburg, J. A., Muenchrath, D. A., White, C. S., S. E. Williams, C. I. Havener, and P. D. Stahl
2002 Soil knowledge embodied in a Native American Runoff Agroecosystem. Transactions of the 17th World Congress of Soil Science, Bangkok, Thailand.

Sandor, Jonathan A., Jay B. Norton, Jeffrey A. Homburg, Deborah A. Muenchrath, Carleton S. White, Stephen E. Williams, Celeste I. Havener, and Peter D. Stahl
2007 Biogeochemical Studies of a Native American Runoff Agroecosystem. *Geoarchaeology* 22(3): 359–386.

Sawyer, John and Antonio Mallarino
2007 Electronic document. http://www.ipm.iastate.edu/ipm/icm/2007/8-6/nutrients.html, accessed October 25, 2009.

Saxton, K.E. and W.J. Rawls
2006 Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society of America Journal* 70: 1569-1578.
Schick, A. P.
1988 Hydrologic Aspects of Floods in Extreme Arid Environments. *Flood Geomorphology,* edited by Victor Baker, Craig Hochel, and Peter Patton, pp189-204. New York, Wiley.

Schimel, D. S., M. A. Stillwell, and R. G. Woodmansee
1985 Biogeochemistry of C, N, and P in a soil catena of the shortgrass steppe. *Ecology* 66:276-282.

Schlesinger, William H., T. J. Ward, and John Anderson
1999 Nutrient losses in runoff from grassland and shrubland habitats in Southern New Mexico: I. rainfall simulation experiments I. *Biogeochemistry* 45: 21-34.

2000 Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: II. Field plots. *Biogeochemistry* 49: 69-86.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson (editors)
2002 *Field book for describing and sampling soils, Version 2.0*. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schollmeyer, Karen Gust
2009 *Resource Stress and Settlement Pattern Change in the Eastern Mimbres Area.* Ph.D. dissertation, Arizona State University.

Schollmeyer, Karen Gust and Margaret C. Nelson
2013 Architecture, Settlement, and the Construction of Perry Mesa Pueblos. In *Alliance and Landscape: 13th and 14th Century Occupation of the Perry Mesa Region of Central Arizona.* Edited by David R. Abbott and Katherine A. Spielmann. University of Utah, Salt Lake.

Scott, Russell L., W. James Shuttleworth, Timothy O. Keefer, and Art W. Warrick
2000 Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest. *Water Resources Research* 36(8):2233-2247.

Shackley, M. Steven
2005 Source Provenance of Obsidian Artifacts from Late Period Sites in the Perry Mesa Area, Central Arizona. Report prepared for the Center for Desert Archaeology, Tucson, Arizona.

2009 The Topaz Basin Archaeological Obsidian Source in the Transition Zone of Central Arizona. Geoarchaeology 24(3):336-347.

Sharpley, A.N.
1985 The selective erosion of plant nutrients in runoff. *Soil Science Society of America Journal* 49:1527-1534.

Shaw, R.H.
1985 Climate Requirement. In *Corn and Corn Improvement*, 3rd. ed., edited by G.F. Sprague and J.W. Dudley. Agronomy Monograph 18:609-638. American Society of Agronomy, Madison, WI.

Sheppard P.R., A.C. Comrie, G.D. Packin, K. Angersbach, and M. Hughes
2002 The climate of the US Southwest. *Climate Research* 21: 219–238.

Shinners, Kevin J., and Ben N. Binversie
2007 Fractional Yield and Moisture of Corn Stover Biomass Produced in the Northern US Corn Belt. *Biomass & Energy* 31:576-584.

Shreve, F.
1934 Rainfall, runoff, and soil moisture under desert conditions. *Annals of the Association of American Geographers* 24:131–156.

Smith, Michael E. and T. Jeffery Price
1994 Aztec-Period Agricultural Terraces in Morelos, Mexico: Evidence for Household-Level Agricultural Intensification. *Journal of Field Archaeology* 21(2): 169-179.

Smith, Susan J.
2007 Pollen Analysis of Agricultural Terraces on Perry Mesa, Yavapai County, Arizona. Report submitted to the Legacies on the Landscape Project. Report on file, School of Human Evolution and Social Change, Arizona State University, Phoenix, Arizona.

2009 Pollen Analysis of Agricultural Terraces on La Plata Mesa, Agua Fria National Monument, Yavapai County, Arizona. Report submitted to the Legacies on the Landscape Project. Report on file, School of Human Evolution and Social Change, Arizona State University, Phoenix, Arizona.

Sparks, D.L. ed.
1996 Chapter 34: Total carbon, organic carbon and organic matter. Methods of soil analysis: Chemical methods. Madison, WI. Soil Science Society of America. pp.961-1010.

Spielmann, Katherine, Hoski Schaafsma, Sharron Hall, Melissa Kruse, and John Briggs

2011 Legacies on the Landscape: The Enduring Effects of Long-Term Human-Ecosystem Interactions. In *Movement, Connectivity, and Landscape Change: The 25th Anniversary Southwest Symposium,* edited by Margaret Nelson and Colleen Strawhacker, pp. 199-217. University of Press of Colorado, Boulder.

Spoerl, Patricia M.
1984 Prehistoric Fortifications in Central Arizona in *Prehistoric Cultural Development in Central Arizona: Archaeology of the Upper New River Region,* pp.261-276. Southern Illinois University at Carbondale Center for Archaeological Investigations Occasional Paper No. 5. Carbondale.

Spoerl, Patricia M. and George J. Gumerman (editors).
1984 *Prehistoric Cultural Development in Central Arizona: Archaeology of the Upper New River Region.* Southern Illinois University at Carbondale Center for Archaeological Investigations Occasional Paper No. 5. Carbondale.

Sprent, Janet I. and Peter Sprent
1990 *Nitrogen Fixing Organisms: Pure and Applied Aspects.* Chapman and Hall, New York.

Stephen, Alexander M.
1936 *Hopi Journal of Alexander M. Stephen,* edited by E.C. Parsons. Colorado University Contributions in Anthropology, 23. Colombia University Press, New York.

Stevenson, Matilda C.
1904 *The Zuni Indians.* 23rd Annual Report for the Years 1901-1902. Bureau of American Ethnology, Smithsonian Institute, Washington, D.C.

Stone, Connie L.
2000 The Perry Mesa Tradition in Central Arizona: Scientific Studies and Management Concerns. In *Archaeology in West-Central Arizona: Proceedings of the 1996 Arizona Archaeological Council Prescott Conference*, edited by T. N. Motsinger, D. R. Mitchell and J. M. McKie, pp. 205-214. Sharlot Hall Museum Press, Prescott.

Sullivan, Allan P.
2000 Effects of Small-Scale Prehistoric Runoff Agriculture on Soil Fertility: The Developing Picture from Upland Terraces in the American Southwest. *Geoarchaeology* 15(4):291-313.

Tate, Robert L.
2000 *Soil Microbiology.* John Wiley & Sons, Inc, New York.

Tolk, Judy A.

2003 Soils, Permanent Wilting Points. In *Encyclopedia or Water Science*, edited by Bobby Alton Stewart and Terry A. Howell, pp 927-929. Marcel Dekker, Inc. New York.

Topp, G.C., J.L. Davis, and A.P. Annan
1980 Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research* 16:574–582.

Trujillo, Jolene
2011 Effects of Prehistoric Agriculture on Modern Biogeochemistry across Gradients of Precipitation and Land Use Intensity. MS, Arizona State University, Tempe, AZ.

Turnbull, Laura
2009 Ecohydrological interactions across a semi-arid grassland to shrubland transition. Ph.D. dissertation, University of Sheffield.

Turnbull, Laura, John Wainwright, and Richard E. Brazier
2010 Changes in hydrology and erosion over a transition from grassland to shrubland. *Hydrological Processes* 24:393-414.

Turnbull, Laura, John Wainwright, and Richard E. Brazier
2011 Nitrogen and phosphorus dynamics during runoff events over a transition from grassland to shrubland in the south-western United States. *Hydrological Processes* 25: 1–17.

Uhart, Sergio Adolfo and Fernando Hector Andrade
1995 Nitrogen Defeciency in Maize: I. Effects on Crop Growth, Development, Dry Matter Partitioning, and Kernel Set. *Crop Science* 35(5): 1376-1383.

Vandermeer, John
1989 *The Ecology of Intercropping.* Cambridge University Press, New York.

Van West, Carla R.
1994 *Modeling Prehistoric Agricultural Productivity in Southwestern Colorado: A GIS Approach.* Reports of Investigations No. 67. Department of Anthropology, Washington State University, Pullman, and Crow Canyon Archaeological Center, Cortez, Colorado.

Van West, Carla R. and Jeffery H. Altschul
1994 Agricultural Productivity and Carrying Capacity in the Tonto Basin. In *The Roosevelt Rural Sites Study: Changing landuse in the Tonto Basin*, edited by Richard Ciolek-Torrello and John R. Welch, pp 361-434. Statistical Research Technical Series No. 28, Volume 3. Tucson.

1997 Environmental Variability and Agricultural Economics along the Lower Verde River, A.D. 750-1450. In *Vanishing River: Landscapes and Lives of the Lower Verde Valley: The Lower Verde Archaeological Project: Overview, Synthesis, and Conclusions.* Edited by Stephanie M. Whittlesey, Richard Ciolek-Torrello, and Jeffery H. Altschul, pp 337-392. SRI Press, Tucson.

Van West, Carla R. and David H. Greenwald
2005 Introduction and Background. In *Fence Lake Project: Archaeological Data Recovery in the New Mexico Transportation Corridor and First Five-Year Permit Area, Fence Lake Coal Mine Project, Catron County, New Mexico, Volume 1: Introduction and Site Descriptions*, edited by E.K. Huber and C.R. Van West, pp. 1.1-1.121. Technical Series No. 84. Statistical Research, Inc., Tucson.

Varien, Mark D.
1996 *Semitism and Mobility in a Social Landscape: Mesa Verde and Beyond*. University of Arizona Press, Tucson.

Wani, S.P., P. Pathak, L.S. Jangawad, H. Eswaran and P. Singh
2003 Improved management of Vertisols in the semiarid tropics for increased productivity and soil carbon sequestration. Soil Use and Management (19) 217-222.

Watkins, Christopher N. and Sophia E. Kelly
2013 Plain Ware Pottery Production and Exchange: Implications for Alliance and Landscape in central Arizona. *Alliance and Landscape: 13th and 14th Century Occupation of the Perry Mesa Region of Central Arizona.* Edited by David R. Abbott and Katherine A. Spielmann. University of Utah, Salt Lake.

Watkins, Christopher N., F. Michael O'Hara, Jessica Walter, Grant Fahrni, and Chris North
2012 *A Cultural Resources Survey of 61.22 miles (371.03 acres) of Federal and State Land for the Arizona Public Service M-001a (Deer Valley to Sycamore0 69kV Transmission line in Maricopa and Yavapai Counties, Arizona.* Logan Simpson Design Technical Report 075107(M-001a). Tempe.

Wells, Christian
2003 *The Archaeology of Dry-Farming Agrosystems in the Middle Gila River Basin, Central Arizona*. Pima-Maricopa Irrigation Project Technical Report No. 2001-07. Cultural Resource Management Program, Gila River Indian Community, Sacaton, Arizona.

Welter, Jill R., Stuart G. Fisher, and Nancy B. Grimm
2005 Nitrogen transport and retention in an arid land water shed: influence of storm characteristics on terrestrial aquatic linkages. *Biochemistry* 76:421-440.

Wendt, G. E., P. Winkelaar, C. W. Wiesner, L. D. Wheeler, R. T. Meurisse, A. Leven, and T. C. Anderson.

1976 Soil Survey of Yavapai County, Arizona, Western Part. United States Department of Agriculture, Soil Conservation Service and Forest Service in cooperation with Arizona Agricultural Experiment Station. Washington, D.C.

Western Regional Climate Center (WRCC), Desert Research Institute

2009 Arizona Climate Summaries Electronic Document, http://www.wrcc.dri/edu/, accessed Sept 30, 2009.

Wilcox, David R. and James Holmlund

2007 *The Archaeology of Perry Mesa and Its World*. Bilby Research Center, Northern Arizona University, Occasional Papers No. 3, Flagstaff, Arizona.

Wilcox, David R., Gerald J. Robertson Jr., and J. Scott Wood

2001a Organized for War: The Perry Mesa Settlement System and Its Central-Arizona Neighbors. In *Deadly Landscapes: Case Studies in Prehistoric Southwestern Warfare*, edited by Glen E. Rice and Steven A. LeBlanc, pp. 141-194. University of Utah Press, Salt Lake City.

2001b Antecedents to Perry Mesa: Early Pueblo III Defensive Refuge Systems in West-Central Arizona. In *Deadly Landscapes: Case Studies in Prehistoric Southwestern Warfare*, edited by G. E. Rice and S. A. LeBlanc. Pp. 109-140. University of Utah Press, Salt Lake City.

Wilcox, David R., Joseph P. Vogel, Tom and Sue Weiss, and Neil Weintraub

2008 The Hilltop Defensive and Communication System of the Greater Prescott Area, A. D. 1100 to 1275, and Their Cohonina Neighbors. In *Presott to Perry Mesa: 4,000 Years of Adaptation, Innovation, and Change in Central Arizona,* edited by Christine K. Robinson, Cory Dale Breternitz and Douglas R. Mitchell, pp. 16.1-16.39. Sharlot Hall Museum Press, Prescott.

Wilken, Gene C.

1987 *Good Farmers: Traditional Agricultural Resource Management in Mexico and Central America.* University of California Press, Berkley.

Williams, John D. and John C. Buckhouse

1991 Surface Runoff Plot Design for Use in Watershed Research. *Journal of Range Management* 44(4):411-412.

Wood, Scott

In review Antecedents II: A Progress Report on the Origins of the Perry Mesa Settlement and Conflict Management System. Manuscript submitted to *The Journal of Arizona Archaeology.*

Woodbury, Ray B.
1961 Prehistoric Agriculture at Point of Pines, Arizona. Memoirs of the Society for American Archaeology 17. *American Antiquity* 26 (3, part 2).

Woosley, A. I.
1980 Agricultural Diversity in the Prehistoric Southwest. *Kiva* 45(4): 317-335.

Zahran, Hamdi Hussein
1999 *Rhizobium*-Legume Symbiosis and Nitrogen Fixation under Sever Conditions and in an Arid Climate. *Microbiology and Molecular Biology Reviews* (63)4: 968-989.

APPENDIX A

SOIL PROFILE CHARACTERISTICS FROM FIELD EXCAVATION OF THE BULL TANK AGRICULTURAL FIELD

Table A.1. Physical properties of excavated terrace trenches.

ID	Strat.	Depth (cm)	Thick. (cm)	Munsell Color (Wet)	Coarse Frags. (%)	Texture (Moist)	Structure Type	Structure Grade	Structure Size Class	Boundary
Trench 1 Terrace 1	A	0-2	2	7.5 YR 2.5/2	20	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	2-9	7	7.5 YR 2.5/2	20	Clay Loam	Angular Blocky	Moderate	Very Fine	Abrupt wavy
	Bt2	9-24.5	15.5	7.5 YR 2.5/3	5	Silty Clay	Angular Blocky, Massive	Strong	Medium	Abrupt wavy
Trench 1 Terrace 2	A	0-2.5	2.5	7.5YR 3/3	3	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	2.5-7.5	5	7.5YR 2.5/2	30	Silty Clay Loam	Angular Blocky	Moderate	Fine	Abrupt smooth
	Bt2	7.5-19.5	12	7.5 YR 2.5/3	50	Silty Clay Loam	Angular Blocky, Massive	Moderate	Coarse	Abrupt Wavy
Trench 3 Terrace 3	A	0-3	3	7.5 YR 4/4	3	Silt Loam	Granular	Weak	Fine	Abrupt smooth
	Bt1	3-10	7	7.5 YR 3/3	5	Clay Loam	Angular Blocky	Moderate	Fine	Abrupt smooth
	Bt2	10-31	21	7.5 YR 3/3	15	Clay Loam	Angular Blocky, Massive	Moderate	Coarse	Abrupt Wavy
Trench 3 Terrace 4	A	0-3.5	3.5	7.5 YR 3/3	5	Silt Loam	Granular	Moderate	Fine	Abrupt smooth
	Bt1	3.5-16.5	13	7.5 YR 2.5/2	10	Silty Clay Loam	Angular Blocky, Massive	Moderate	Medium	Abrupt wavy
	Bt2	16.5-44	27.5	7.5 YR 3/3	10	Clay Loam	Massive	--	--	Abrupt wavy
Trench 5 Terrace 5	A	0-3	3	7.5 YR 2.5/2	1	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt	3-8	5	7.5 YR 3/3	1	Loam	Angular Blocky	Moderate	Fine	Abrupt smooth
Trench 5 Terrace 6	A	0-4	4	7.5 YR 3/3	1	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	4-13	9	10 YR 3/3	5	Loam	Angular Blocky	Moderate	Fine	Abrupt wavy
	Bt2	13-25	12	7.5 YR 2.5/3	10	Clay Loam	Angular Blocky, Massive	Moderate	Coarse	Abrupt wavy
Trench 7 Terrace 7	A	0-4	4	7.5 YR 3/3	3	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	4-13	9	7.5 YR 2.5/3	10	Silty Clay Loam	Angular Blocky	Moderate	Medium	Abrupt wavy
	Bt2	13-28	15	7.5 YR 3/3	20	Silty Clay	Massive	--	--	Abrupt wavy
Trench 7 Terrace 8	A	0-4	4	7.5 YR 2.5/3	1	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	4-13	9	7.5 YR 2.5/3	1	Silty Clay Loam	Angular Blocky	Moderate	Medium	Abrupt wavy
	Bt2	13-25	12	7.5 YR 2.5/3	5	Silty Clay Loam	Angular Blocky, Massive	Moderate	Very Coarse	Abrupt wavy

Table A.2. Physical properties of excavated non-terrace trenches.

ID	Strat	Depth (cm)	Thick. (cm)	Munsell Color (Wet)	Coarse Frags. (%)	Texture (Moist)	Structure Type	Structure Grade	Structure Size Class	Boundary
Trench 2	A	0-3	3	7.5 YR 5/3	5	Silt Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	3-8.5	5.5	7.5 YR 5/3	5	Silty Clay	Angular blocky	Moderate	Fine	Abrupt wavy
	Bt 2	8.5-19	10.5	7.5 YR 4/3	5	Silty Clay Loam	Angular blocky, Massive	Strong	Coarse	Abrupt wavy
Trench 4	A	0-5	5	7.5 YR 4/3	2	Clay Loam	Granular	Moderate	Fine	Abrupt smooth
	Bt1	5-15	10	7.5 YR 2.5/2	5	Silty Clay	Angular blocky	Moderate	Medium	Abrupt wavy
	Bt2	15-30	15	7.5 YR 2.5/2	5	Silty Clay	Massive	--	--	Abrupt wavy
	Bt3	30-45	15	7.5 YR 2.5/2	5	Silty Clay	Massive	--	--	Abrupt wavy
Trench 6	A	0-3	3	7.5 YR 4/3	40	Clay Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	3-9	6	7.5 YR 3/2	5	Silty Clay	Angular blocky	Moderate	Fine	Abrupt smooth
	Bt2	9-20	11	7.5 YR 4/3	20	Silty Clay	Angular blocky, Massive	Moderate	Medium	Abrupt wavy
Trench 8	A	0-3	3	7.5 YR 4/3	5	Silty Clay Loam	Granular	Weak	Very Fine	Abrupt smooth
	Bt1	3-8	5	7.5 YR 3/ 4	5	Silt Loam	Angular blocky	Moderate	Fine	Abrupt smooth
	Bt2	8-30	22	7.5 YR 2.5/3	2	Silty Clay	Angular blocky	Strong	Coarse	Clear smooth
	Bt3	30-54	24	7.5 YR 2.5/3	2	Silty Clay	Angular blocky, Massive	Strong	Very Coarse	Abrupt wavy

Table A.3. Bulk density, soil particle size and water holding capacity (WHC) from excavated terrace and terrace and non-terrace trenches.

Context	Stratum	Bulk Density g cm^{-3}	Sand %	Silt %	Clay %	WHC %
Terrace						
Trench 1 Terrace 1	A	1.17	24.6	51.76	23.63	17.81
	Bt1	1.84	21.55	45.43	33.02	19.76
	Bt2	1.95	15.26	42.45	42.29	20.61
Trench 1 Terrace 2	A	1.55	16.61	56.71	26.68	18.51
	Bt1	1.89	17.98	48.03	33.99	19.54
	Bt2	2.2	18.79	44.37	36.84	19.12
Trench 3 Terrace 3	A	1.39	25.49	53.69	20.82	16.83
	Bt1	1.75	22.89	44.01	33.10	19.06
	Bt2	1.72	15.81	38.74	45.45	22.62
Trench 3 Terrace 4	A	.91	27.25	51.93	20.82	16.81
	Bt1	1.61	19.08	45.32	35.60	21.13
	Bt2	1.95	10.12	32.34	57.53	24.20
Trench 5 Terrace 5	A	1.41	30.36	56.06	13.57	14.29
	Bt1	2.31	31.06	44.34	24.60	15.19
Trench 5 Terrace 6	A	1.3	33.03	53.14	13.84	16.45
	Bt1	2.01	33.6	42.95	23.46	17.95

Context	Stratum	Bulk Density g cm^{-3}	Sand %	Silt %	Clay %	WHC %
	Bt2	N/A	27.13	36.86	36.02	20.41
Trench 7 Terrace 7	A	1.22	23.12	54.81	22.08	17.12
	Bt1	1.76	19.95	45.94	34.12	18.33
	Bt2	1.92	17.94	40.07	41.98	21.61
Trench 7 Terrace 8	A	1.1	21.88	57.41	20.71	16.90
	Bt1	N/A	19.65	48.69	31.65	19.20
	Bt2	1.71	18.87	42.75	38.38	20.74
Non-Terrace						
Trench 2	A	1.18	24.79	59.61	15.60	16.35
	Bt1	N/A	10.24	46.98	42.78	21.26
	Bt2	1.95	16.22	43.94	39.84	20.61
Trench 4	A	.69	20.46	47.05	32.49	20.19
	Bt1	1.84	14.88	40.81	44.31	22.63
	Bt2	1.86	13.34	42.38	44.27	24.74
	Bt3	1.80	13.13	44.30	42.58	20.62
Trench 6	A	1.52	23.78	43.32	32.90	19.60
	Bt1	1.61	18.13	40.64	41.22	21.47
	Bt2	1.73	16.54	41.11	42.35	20.64
Trench 8	A	1.30	15.59	52.07	32.35	21.12
	Bt1	1.81	21.72	52.06	26.21	21.03
	Bt2	1.79	11.51	47.50	40.98	18.24
	Bt3	1.96	8.60	46.97	44.43	21.96

Table A.4. Soil organic matter and nutrient concentrations from excavated terrace trenches.

Context	Stratum	Organic Matter %	Available P	Total C	Total N	C:N
Terrace						
Trench 1 Terrace 1	A	4.36	34.80	10.56	0.97	10.89
	Bt1	3.41	17.20	7.715	0.74	10.43
	Bt2	4.62	15.40	7.52	0.77	9.77
Trench 1 Terrace 2	A	4.19	33.40	9.11	0.85	10.72
	Bt1	4.28	22.20	8.27	0.79	10.47
	Bt2	4.38	16.00	7.72	0.75	10.29
Trench 3 Terrace 3	A	6.20	34.00	8.18	0.75	10.49
	Bt1	4.31	20.00	7.2	0.73	9.86
	Bt2	4.86	16.60	8.01	0.81	9.96
Trench 3 Terrace 4	A	4.69	31.20	17.655	1.665	10.60
	Bt1	4.93	17.80	10.68	1.09	9.80
	Bt2	5.37	2.60	7.87	0.83	9.48
Trench 5 Terrace 5	A	3.32	48.60	8.48	0.85	9.98
	Bt1	3.32	33.60	6.62	0.67	9.88
Trench 5 Terrace 6	A	3.96	33.40	11.72	1.11	10.55
	Bt1	3.59	22.2	7.79	0.76	10.25
	Bt2	4.63	16.60	7.61	0.76	10.01
Trench 7	A	4.07	19.60	11.02	1.08	10.20

Context	Stratum	Organic Matter %	Available P	Total C	Total N	C:N
Terrace 7	Bt1	4.19	3.0	8.25	0.82	10.06
	Bt2	4.67	2.0	8.42	0.82	9.78
Trench 7 Terrace 8	A	4.59	20.0	8.6	0.86	10.00
	Bt1	4.03	5.60	7.42	0.75	9.89
	Bt2	4.15	1.80	6.71	0.65	10.32
Non-Terrace						
Trench 2	A	3.94	34.60	10.07	0.98	10.28
	Bt1	4.70	15.40	7.93	0.71	11.24
	Bt2	4.84	15.80	8.55	0.85	10.06
Trench 4	A	4.78	28.00	12.54	1.18	10.63
	Bt1	4.78	17.00	9.7	0.89	10.90
	Bt2	4.55	16.20	7.77	0.75	10.36
	Bt3	4.43	1.60	6.74	0.65	10.37
Trench 6	A	4.16	27.40	8.47	0.87	9.74
	Bt1	4.61	20.00	7.55	0.74	10.20
	Bt2	4.51	16.80	7.62	0.71	10.73
Trench 8	A	5.75	20.60	15.81	1.44	10.98
	Bt1	4.77	8.20	9.13	0.88	10.38
	Bt2	4.25	12.2	8.99	0.91	9.88
	Bt3	4.42	1.60	7.13	0.67	10.64

APPENDIX B

PERMANENT WILTING POINT AND FIELD CAPACITY

In order to contextualize the results, the graphs in Chapter 5 display a line representing the field capacity (FC) and a line representing the permanent wilting point (PWP; Figures 6.3, 6.4). Soil water content between these two ranges is the most ideal for plant growth. The graphed FC value of 38% and PWP value of 22% are the baseline estimates for a silty clay loam soil (Saxton and Rawls 2006), the textural class of most of the lower soil profiles at Bull Tank. A soil is at FC after excess water has drained away and the rate of downward movement within the soil has materially ceased (Nachabe et al. 2003). This concept is useful because it defines the maximum amount of water that is useful to plants; water content above FC has insufficient air-filled pore space to allow for aerobic microbial activity and plant growth (Brady and Weil 2007). The range of soil moisture between a soil's FC and PWP is the amount of water available for root uptake, called the available water capacity or content (AWC). The drier the soil becomes, the more tightly the remaining water is held around individual soil particles and the more difficult it is for the plant roots to extract it. At a certain stage, the uptake of water is not sufficient to meet the plant's needs. The plant loses freshness and wilts; the leaves change color from green to yellow; and finally the plant dies. The soil water content at the stage where the plant dies is called permanent wilting point (PWP; Tolk 2003). The soil still may contain some water, but it is too difficult for the roots to draw it from the soil. If moisture decreases to the PWP a plant cannot recover.

The FC and PWP values are dependent upon soil structure, organic matter content, rock fragments, electrical conductivity, and texture. Therefore, every soil has unique characteristics that determine these dynamics. However, strong statistical correlations exist between FC and PWP and soil texture and this is often used as an estimate of field conditions (Saxton and Rawls 2006; Table 6.1). In general, increases in clay content lead to increases the FC and PWP. Clay particles hold water much more tightly than coarser particles, which are larger. Water is held in films around individual soil particles and because clay particles are smaller, water is spread thinner across more particles (Brady and Weil 2007). Therefore, water may be present in a soil high in clay, but inaccessible to plants because the water is held too tightly within the small pore spaces. Increases in coarser particles allow more water to be accessed by plants but more drainage occurs in coarse soils and thus FC, the amount of water that can be held, is lower. This is why a medium textured soil, like a silt loam, has the greatest potential for water availability (high FC and low PWP; Brady and Weil 2007).

Table B.1. Field capacity and permanent wilting point for soil texture classes (after Saxton and Rawls 2006).

Texture Class	Sand	Clay	$PWP_{-1.5}$	FC
	% wt.		% vol.	
Sand	88	5	5	10
Loamy Sand	80	5	5	12
Sandy Loam	65	10	8	18
Loam	40	20	14	28
Silt Loam	20	15	11	31
Silt	10	5	6	30
Sandy Clay Loam	60	25	17	27
Clay Loam	30	35	22	36
Silty Clay Loam	10	35	22	38
Silty Clay	10	45	27	41
Sandy Clay	50	40	25	36
Clay	25	50	30	42

PWP, in particular, also depends upon plant type. PWP is often estimated as the water content of the soil at -1.5 MPa soil matric potential (represented as PWP $_{-1.5}$). Many plants' wilting points are similar to the -1.5 PWM estimate and therefore this is a good general proxy (Tolk 2003). However, some agricultural plants have a higher PWP threshold. For example, Tolk (2003) determined that PWP for sorghum was similar to the PWP $_{-1.5}$ but significantly higher for hybrid corn. When the volumetric soil water content of the soil profile was converted to millimeters, the PWP for corn was 488 mm, 420 mm for sorghum, and the PWP$_{-1.5}$ was 398 mm indicating that corn would wilt and die with approximately 100 mm more water than the estimated PWP$_{-1.5}$ (Tolk 2003:929). The PWP for indigenous Southwestern corn varieties is unknown. Presumably indigenous varieties were much more tolerant to dry conditions than modern hybrids and therefore likely to have PWP closer to the PWP$_{-1.5}$ estimate. However, future research is needed to generate baseline data about water usage of Southwestern cultigens.

APPENDIX C

SUPPLEMENTAL RESULTS OF THE RUNOFF COLLECTION STUDY

This appendix presents background about the natural rainfall characteristics observed during the runoff collection study discussed in Chapter 6. Additional analyses presented include several that explore and compare runoff discharge between the different collection contexts, runoff nutrient content, and the particle sizes of sediment transported by runoff.

Rainfall Characteristics during Runoff Study Monitoring

Due to an extremely dry 2009 summer season in the Agua Fria watershed, no runoff events were observed once the collection protocol was fully functioning. An estimated 13 mm (0.5 in) rainfall event occurred in the Bull Tank area when only a portion of runoff collection equipment was present. While no runoff was collected from this event it did allow for problem solving and refinement of the installation processes. All of the equipment was installed by August 14, 2009 and after this data an additional 11 mm (0.43 in) fell during 6 events that produced no runoff. For the entire state of Arizona, 2009 was the 6th driest on record since 1896. The El Niño-Southern Oscillation (ENSO) is credited with suppressing monsoon rains (CLIMAS 2009). Despite this collection period being unproductive in terms of runoff generation, it did allow for experimentation with logistics and refinement of collection procedures.

El Niño conditions produced high total rainfall during the 2010 winter collection period. Nearly 152.0 mm (6 in) fell during a 36 hour period in late January and it continued to rain heavily for several more days. The high streamflow present in the Agua Fria River prevented access to Bull Tank immediately after these events and the collection units were not accessed for several days. Regardless, all but one runoff collection units was damaged during this high rainfall event, likely due to the extreme runoff that it produced.

Thirty percent of monitored 2010 winter rain events produced runoff. The lowest total rainfall event that produced runoff during the winter occurred on February 7 when antecedent conditions were extremely moist. This event, 12 mm (0.47 in) total, produced runoff in 15 units (6 viable samples >50ml). All other winter rainfall events that produced runoff were at least 20-44 mm total (0.79-1.73 in). Overall rainfall intensity of winter storms that produced runoff ranged from 1.7 mm/hr to 8.0 mm/hr, intensities that were less than most summer rainfall events. Given the long duration of winter rainfall, it is likely that rainfall intensities fluctuated throughout the duration of the event.

During the 2010 summer monsoon collection period, there were once again drier-than-average conditions for the end of the monsoon season (CLIMAS 2010b). Late July and August produced between 90-120% of average precipitation for central Arizona and alleviated short-term drought conditions (CLIMAS 2010a). Most rainfall events during the summer 2010 collection period occurred before August 31, with September being relatively dry. Moisture from tropical storms in the Pacific Ocean did result in a few rainfall events and subsequent runoff events in early October.

Most observed rainfall events during the summer collection periods came as minor, non-runoff generating events (71%). This is typical for the long-term daily precipitation data from other weather stations in the region, which indicate that approximately 25% of all summer dates with recorded rainfall are greater than 0.25 inches. A majority of rainfall events result in just a trace amount of precipitation.

Summer precipitation is part of the North American Monsoon that occurs from July 1 through September 30. The monsoon is typically very spatially variable because it tends to generate highly localized thunderstorms (Goodrich et al. 1995; 2008; Hastings et al. 2005). Even if a thunderstorm is over a particular area, rainfall can vary immensely within the cell resulting in significantly different recorded intensities and amount. For example, mean rainfall amount, or depth, and intensities of summer monsoon events were observed to vary by as much as 4 to 14% within a 100-m distance in southern Arizona (Goodrich et al. 1995). Measurements from a single rain gauge can lead to large uncertainties concerning rainfall dynamics, which has important implications for modeling runoff (Faures et al. 1995, Goodrich et al. 1995; Hastings et al. 2005). Daily radar observations during the collection period support this characterization. It was common for storms to be observed in the larger Perry Mesa area but rare for the thunderstorm cell to pass over the Bull Tank field. Additionally, thunderstorm cells that did pass over the Bull Tank area did not always result in much rainfall accumulation.

The lowest total precipitation amount (depth) that generated runoff collections for more than one collection unit during the summer was 11 mm (0.43 in) on 9/22/2010. Runoff was recovered from only one unit from a rainfall event totaling 7.6mm (0.3 in), however most storms of this quantity or lower did not result in runoff. Rainfall intensity of storms that produced runoff in the summer ranged from 3.8 mm/hr to 25.7 mm/hr. Rainfall amounts producing substantial runoff were 11 mm to 35.4 mm (0.43 to 1.39 in).

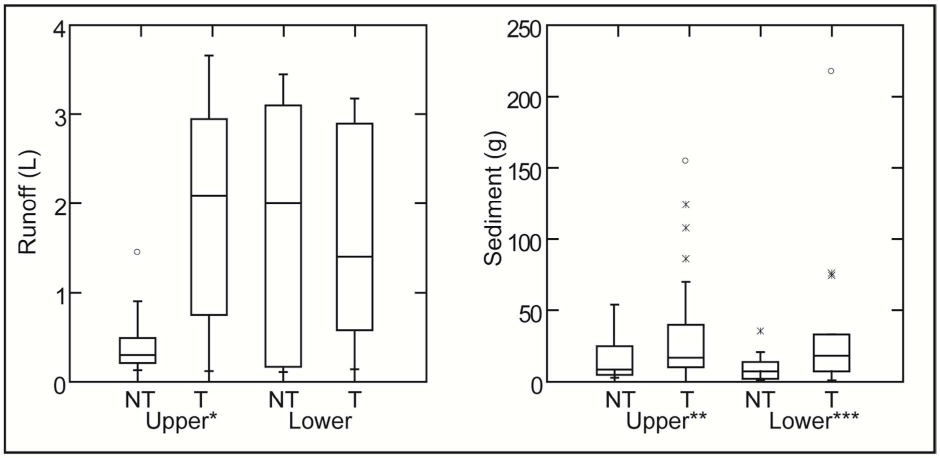
Runoff Discharge and Collection Context

Significant differences between non-terrace and terrace unit runoff volume discharge exist for upper locations but runoff volume was similar between non-terrace and terraces in lower slope units (Figure C.1). Non-terrace units in upper locations not only produced runoff less frequently (n=14), runoff discharge volumes were low ($\bar{x}$=0.421 L) in comparison to upper terrace units which produced 39 runoff samples averaging 1.941 L. Lower slope non-terrace (n=11) and terrace units (n=17) produced similar volumes of runoff (non-terrace $\bar{x}$=1670; terrace $\bar{x}$= 1610).

The amount of sediment transported in runoff was significantly higher for both upper and lower terrace locations compared to respective non-terrace locations (upper $p=0.008$; lower $p=0.084$). Upper terrace runoff collections yielded 33.69 g of sediment on average whereas non-terrace runoff collections yielded 14.81 g on average. Lower terraces yielded 22.79g on average compared to an average of 10.285g from lower non-terrace locations.

It appears that the greater rock and vegetation cover in non-terrace units intercept runoff, prohibiting runoff flow and sediment moved by the flow. These observations are complementary to others (Schlesinger et al. 1999; Turnbull et al. 2010) who determined that runoff in contexts dominated by shrubs and bare ground was more frequent, larger in volume, and transported more debris compared to those with higher vegetation cover like grasses.

The determination that runoff volume is higher in both lower slope contexts vs. upper non-terrace contexts is likely related to the greater velocity of runoff flow generated by the longer slope distance. This indicates that lower slopes or the base of hills would have greater potential to receive runoff flow vs. locations nearer to the hill summit. However, terracing, more specifically the clearing of rock and vegetation,



*Significant at <0.001, **Significant at 0.05, *** Significant at 0.1

Figure C.1. Box and whisker plots of runoff discharge volume and sediment yield by runoff collection unit location.

increases runoff flow irrespective of slope placement and runoff generated in terrace contexts transports more sediment.

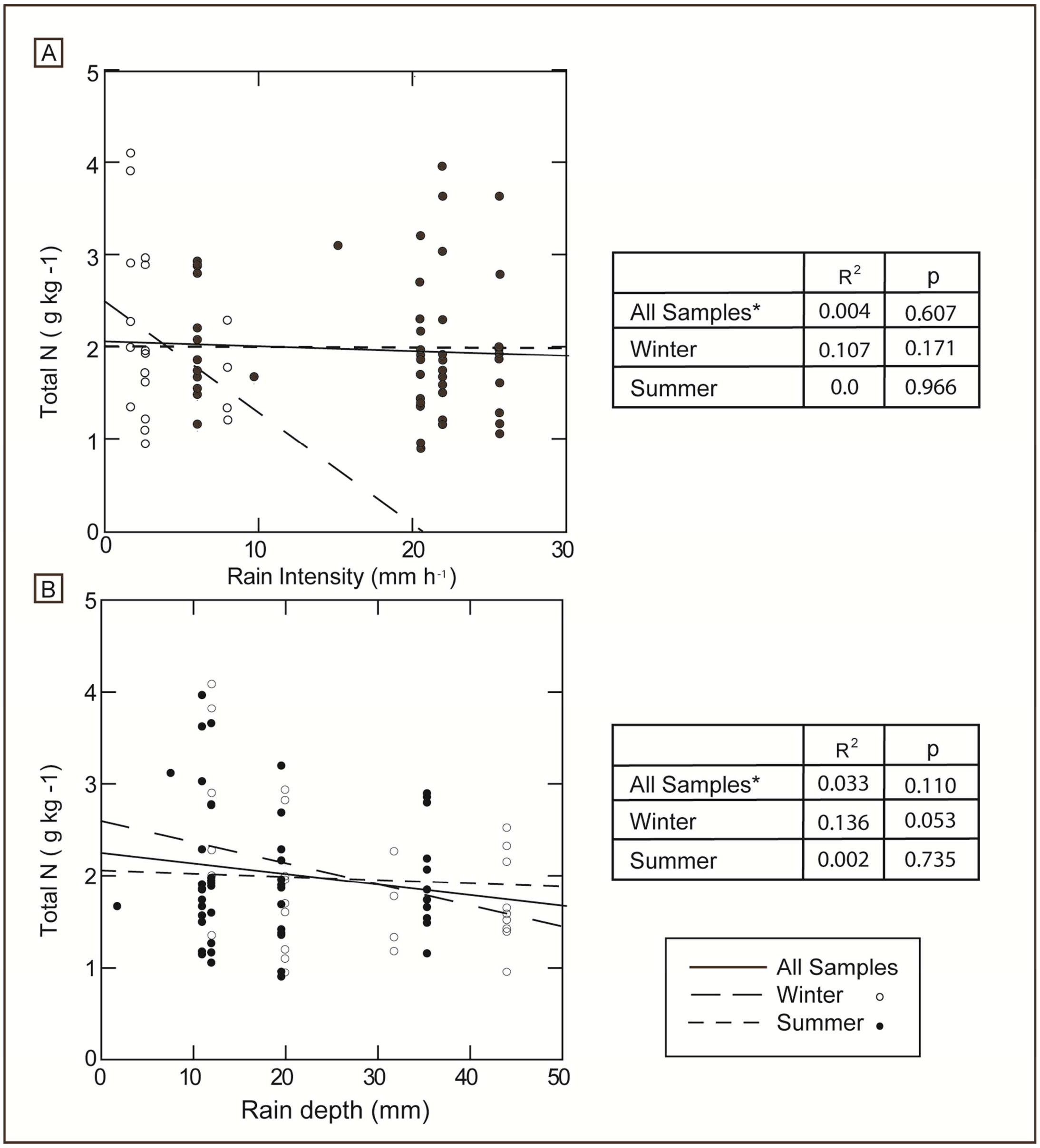
While the collection unit location had a relationship with the likelihood that runoff was produced and the amounts of sediment transported, it is important to remember the relationships between rainfall dynamics and runoff discussed previously. Interestingly, the specific collection units that contained runoff were not always predictable across all rain events. One unit that seemed to always produce runoff during one series of storms would have little to no runoff during the next storm. Specific storm micro patterns as well as surface conditions influence runoff generation but were not the scale of dynamics monitored in this study.

Runoff Nutrients and Rainfall Dynamics

The strength of the relationships between nutrient concentration with the rainfall dynamics of rainfall event date, intensity and depth was determined using Pearson's correlations. Each relationship is graphed as a scatter plot with linear smother to show the data trends. The r^2 and p-values are reported and significance levels were defined at the 0.05, 0.01, and ≤0.001 levels. As with other analyses, this analyses of nutrient concentrations do not include runoff collections that were from more than 1 single rainfall event, collections that likely overflowed collection buckets, or data from collections with <50 ml. Winter and summer events are distinguished in the visual display and were analyzed as separate sample types in the linear regression analysis. However, as shown in Table 5.3, there are no significant differences between nutrient concentrations in winter and summer runoff events.

No clear relationships were observed between TN concentration and rainfall intensity and depth (Figure C.2). Therefore, the simulation model assumed that nutrient concentration does not vary with rainfall dynamics. There are significant relationships between rainfall dynamics and the composition of nutrients, however, measured by the carbon to nitrogen ratio (C/N). This ratio is a proxy for the level of organic matter decomposition. The more decomposed, the higher proportion of nutrients will be bioavailable for plant uptake. The earliest storms in the summer produced the highest quality, or more decomposed organic matter, compared to later season storms. Additionally, the quality of organic matter decreased the greater the rainfall depth and the more intense the storm.

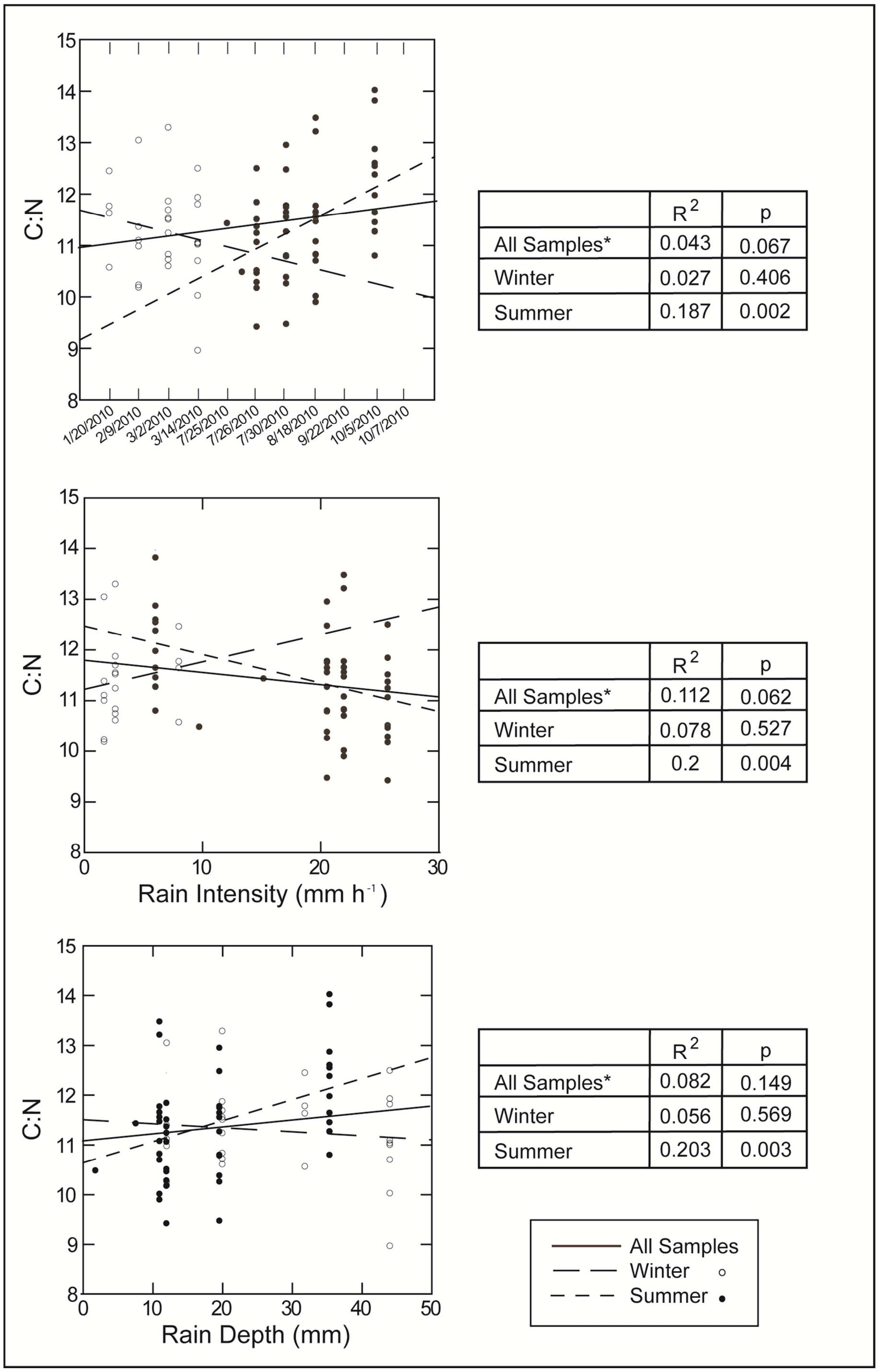
To illustrate the relationships between rainfall dynamics (date, intensity, and amount or depth) and the composition of nutrients contained within runoff, a regression analysis is presented for the carbon to nitrogen (C/N) ratio (Figure C.3). While these relationships are complex, in general, the lower the C/N ratio, the more decomposed the organic matter and the higher the nutrient quality as more will be available in liable



	R^2	p
All Samples*	0.004	0.607
Winter	0.107	0.171
Summer	0.0	0.966

	R^2	p
All Samples*	0.033	0.110
Winter	0.136	0.053
Summer	0.002	0.735

Figure C.2. Relationships between total nitrogen concentrations and rainfall dynamics. Squares in A are statistical outliers. *Outliers removed from analysis.



	R^2	p
All Samples*	0.043	0.067
Winter	0.027	0.406
Summer	0.187	0.002

	R^2	p
All Samples*	0.112	0.062
Winter	0.078	0.527
Summer	0.2	0.004

	R^2	p
All Samples*	0.082	0.149
Winter	0.056	0.569
Summer	0.203	0.003

Figure C.3. Relationships between C/N ratio and rainfall dynamics. *Outliers removed from analysis.

Forms (plant available), ready to be incorporated into plant tissue (Gliesman 2007; Norton et al. 2007; Brady and Weil 2007).

Correlations between nitrogen concentrations and rainfall dynamics, the consideration of relationships between the C/N ratio and rainfall dynamics resulted in low r^2 values because of the high variability of each observed runoff event. Therefore these relationships are interpreted to be weak correlations despite all of the summer relationships being statistically significant at 0.05 level. A positive relationship was observed between C/N ratios over the summer period (Figure C.3: A; $r^2 = 0.187; p=0.002$) indicating that the earlier summer storms had the highest quality organic matter, or the most decomposed. Similar to the dynamics occurring in the Zuni region (Norton et al. 2007a), the lowest C/N ratios occur at the onset of the summer monsoons and increase throughout the season.

Rainfall intensities during the summer are negatively correlated with the C/N ratio with the highest intensity storms producing the lowest C/N ratios (Figure C.3: B; $r^2 = 0.2; p=0.004$). This is opposite the pattern observed in the Zuni area, where C/N ratios increased with storm intensity (Norton et al. 2007a). The Zuni study had more observed runoff events and more intense storms than the present study so conclusions presented here may be less conclusive due to the size of the dataset.

Additionally, rainfall amount or depth during the summer is positively correlated with increasing C/N ratios, indicating the longer it rains, nutrient quality decreases (Figure C.3: C; $r^2 = 0.203; p=0.003$). Collectively these results indicate that during the summer, the first rain storms, the storms that are of lower intensity, and storms of lower quantity produce the highest quality or more decomposed organic matter.

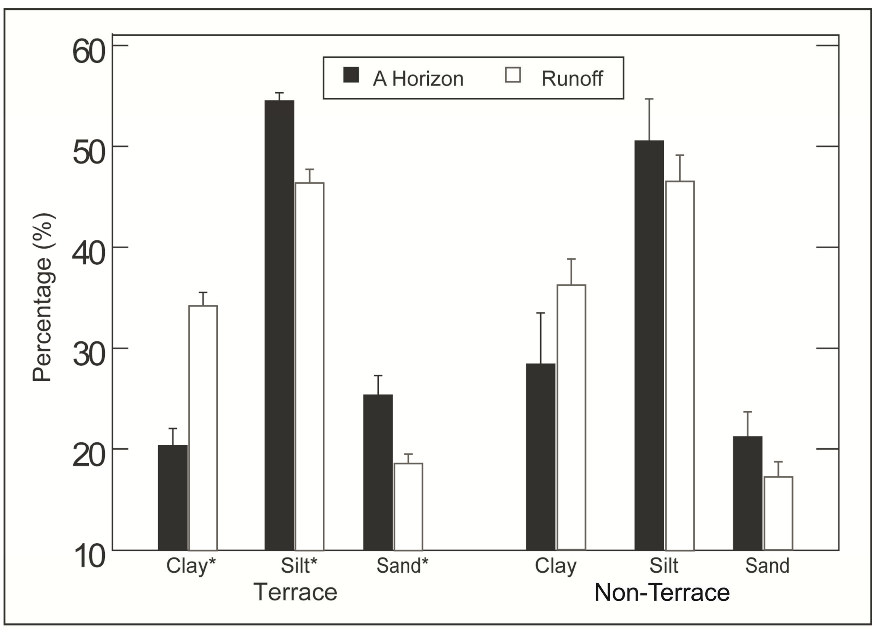
No significant relationships were observed when considering only the winter runoff events. It may be that the narrow range rainfall dynamics occurring during winter runoff producing storms and the overall sample dataset does not vary enough to determine if differences in C/N ratios exist.

Particle Size Characteristics of Runoff Sediments

Particle size distribution, or soil texture, was determined for 32 runoff collection samples. These data were compared with results from the soil samples obtained from the trench excavations discussed in Chapter 4. The hydrometer method (Gee and Or 2002) was used. Samples pretreated with sodium hexametaphosphate solution for clay dispersion. Hydrometer readings followed by sieving to 53 μm for sand fraction and determination of silt fraction by difference. Particle-size distribution is classified as gravels (> 2 mm), Sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (less than 0.002 mm).

Results demonstrate that runoff transports greater amounts of fine clay sediments compared to coarse sediments within the Bull Tank system. The particle-size of sediments provides basic information about the erosional and depositional processes of runoff events. The size of particles detached and transported by overland runoff flow depends upon numerous factors including rainfall intensity, amount or depth, raindrop circumference, hillslope angle, vegetation, ability of soil to form aggregates but typically they are always finer than the matrix soil from which they originate (Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Parsons et al. 1991). Redistribution of soil particles by runoff is one of the main processes of catena development and results in increased silt, clay, organic matter, and nutrients downslope (Ruhe and Walker 1968, Schimel et al. 1985, Burke et al. 1995).

The particle sizes of samples from A Horizons soils from excavated trenches (Chapter 4) and sediments from runoff contexts (n=33) were compared to parent soils (n=12). Because of sample size discrepancies, a Kruskal-Wallis rank analysis was used to determine significance levels (Figure C.4). Particle-size distribution (PSD) was determined for runoff samples that yielded enough sediment for analysis, >40 g. In some instances samples from similar collection units and runoff event dates were aggregated to allow for PSD analysis.



*Significant at 0.01

Figure C.4. Comparison of particle size distribution of A horizons and runoff.

Runoff in terrace contexts contains a significantly higher proportion of clay compared to parent A horizon soils and significantly lower proportions of silt and sand (*p=0.001*). Similar tendencies occur between runoff and A horizons soil from non-terrace contexts but the relationship is not statistically significant and may be influenced by the presence of only 2 non-terraced runoff samples that contained enough sediment for PSD analysis. This is matches previous field and laboratory-based observation that sediments transported by runoff are typically finer than the matrix soil (Jin et al. 2009; Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Parsons et al. 1991; Turnbull et al. 2010). It is the finer fractions that are often mobilized early within a runoff event indicating that small-scale events have the capacity to cumulatively move an abundance of fine fraction material (Palis et al. 1997; Turnbull 2009).

The enrichment of the clay fraction of runoff-transported sediments is likely the result of two factors. First, fine, atmospheric dust often accumulates within the micro topography of the surface and is easily washed off by overland flow (Barger et al. 2006; Reynolds et al. 2001). Recent research has demonstrated that the deposition of dust is largely responsible for the formation of Perry Mesa soils (Nakase 2012). Many atmospheric particles deposited on the landscape would likely immediately proceeded monsoon thunderstorms and would be some of the initial particles transported by runoff flow. Second, a process termed "raindrop stripping" is probably occurring, where the fine particles are more likely to be peeled away from soil aggregates through raindrop impact (Ghadiri and Rose 1991b).

Selective transport of fine sediment during surface runoff is significant because particulate-bound nutrients are primarily associated with fine sediment fractions (Jin et al.

2009; Ghadiri and Rose 1991a, b; Lister 2007; Palis et al. 1997; Ramos et al. 2006). Therefore, the selective transport of fine sediment in runoff is also selectively transporting nutrients. If runoff is captured, this would lead to progressive enrichment of soil due to runoff deposition. However, if runoff is more of an erosive process, nutrient degradation will occur as more fine sediments and nutrients are transported away.

As discussed above, runoff is more frequent and transports greater amounts of sediment in terrace contexts compared to non-terraced contexts due to the ground cover of terraced surfaces (Figures C.1). Therefore, it appears that terraces are not only experiencing a greater loss of fine sediments compared to non-terraced areas, but a greater potential loss of nutrients. It is the management of terraces that would make the difference between runoff as a depositional versus erosive force within the field system and the difference between sediment particles and nutrients as additions versus losses.

Nutrients in Runoff Compared to Matrix Soils

Comparison of nutrient data from Bull Tank A Horizon soils with runoff sediment indicates that runoff sediments have higher nutrient concentrations than their parent matrix (Table C.1; Figure C.5; p=<*0.001*). The C/N ratio differences were not statistically significant ($p=0.163$) indicating the quality, the level of decomposition, is similar to the parent soil.

In general, runoff sediments are more nutrient-enriched compared to matrix soils emphasizing the importance of runoff in nutrient transport due to the tendency of organic matter to be located near the surface and the affinity of soil nutrients to be bound to fine sediment particles, which are proportionally transported by runoff (Jin et al. 2009;

Ghadiri and Rose 1991a, b; Mallam-Issa et al. 2006; Ramos et al. 2006; Sharpley 1985, Tunbull et al. 2011).

Soil data used to compare with data from runoff sediments were collected in June 2009 prior to the summer monsoon season. Ten samples were taken across the upper and lower terraces and non-terrace locations for a total of 40 samples. Two soil cores from each sample location and pooled (0-7 cm depth). This depth represents the A and upper Bt horizons.

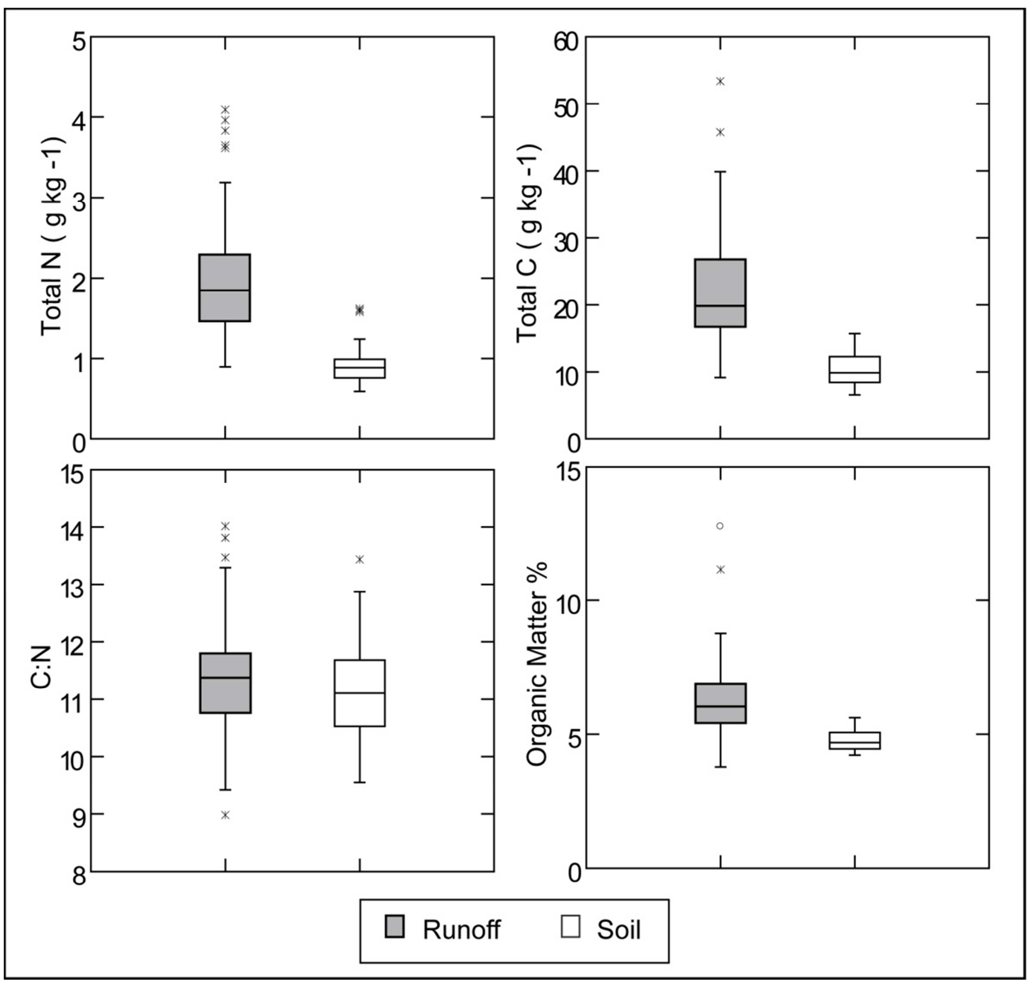


Figure C.5. Nutrient concentration of runoff sediment and surface soils (0-7 cm depth).

An alternative analysis focused on the enrichment ratios indicates a similar conclusion that more nutrients are contained within runoff transported sediments than the parent soils. The enrichment ratios, the ratio of the concentration of a soil component (i.e. total N) in transported sediments to that of the original soil which the sediment originates (Massey and Jackson 1952), indicates that runoff has higher nutrient quantity than parent soils. A ratio greater than 1 suggests enrichment while a ratio of less than 1 suggests runoff is depleted in terms of the variable in question. The Bull Tank ratios of 2.14 for nitrogen and 2.10 for carbon suggest that these nutrients are preferentially transported in similar proportions (Table 5.4).

Table C.1. Comparison of nutrients of sediment transported by runoff (R; n=79) and surface soil (S; 0-7 cm depth; n=40).

		Mean	S.D.	p value	Enrichment Ratio
Total Nitrogen (g/kg^{-1})	R	1.981	0.749	0.000*	2.14
	S	0.925	0.239		
Total Carbon (g/kg^{-1})	R	22.665	9.105	0.000*	2.10
	S	10.254	2.372		
C/N	R	11.387	0.997	0.163	NA
	S	11.145	0.843		
Organic Matter %[a]	R	6.436	1.715	0.000*	1.35
	S	4.77	0.375		

[a]R n=38, S n=40.
*Significant at ≤0.001.

APPENDIX D

RUNOFF COLLECTION DATA

Table D.1. Runoff collection samples, n=82. (W = Winter, S = Summer)

Runoff Collection Unit	Seas.	Runoff Event Date	Event Rainfall Total (mm)	Runoff Volume (ml)	Sediment (g)	Total Nitrogen (g/kg-1)	Total Carbon (g/kg-1)	C/N
LSETB	W	1/20/2010	31.8	855	11.49	1.780	18.840	10.58
USANT	W	1/20/2010	31.8	275	8.68	1.340	16.700	12.46
LSENT	W	1/20/2010	31.8	3370	7.28	2.270	26.430	11.64
USCTB	W	1/20/2010	31.8	920	16.71	1.190	14.010	11.77
USDTB	W	2/9/2010	12.0	630	4.16	1.350	14.990	11.10
LSFNT	W	2/9/2010	12.0	110	0.87	4.090	53.390	13.05
LSENT	W	2/9/2010	12.0	110	2.16	3.830	39.030	10.19
LSETT	W	2/9/2010	12.0	242	0.95	2.290	25.190	11.00
LSETB	W	2/9/2010	12.0	140	1.88	2.910	29.790	10.24
USCTB	W	2/9/2010	12.0	2580	10.79	1.990	22.640	11.38
USATT	W	3/2/2010	20.0	1010	4.52	1.610	17.100	10.62
USDNT	W	3/2/2010	20.0	265	3.54	1.710	22.730	13.29
USATB	W	3/2/2010	20.0	2690		1.210	13.120	10.84
USCTB	W	3/2/2010	20.0	283	13.69	1.990	22.390	11.25
LSETB	W	3/2/2010	20.0	245	2.51	1.960	22.920	11.69
LSETT	W	3/2/2010	20.0	1110	7.30	2.940	33.950	11.55
USBNT	W	3/2/2010	20.0	130	3.62	1.100	13.060	11.87
LSFNT	W	3/2/2010	20.0	160	2.02	2.830	32.630	11.53
LSFTT	W	3/2/2010	20.0	160	7.75	0.955	10.255	10.74
LSFTB	W	3/14/2010	44.0	3045	18.21	1.640	17.560	10.71
LSFNT	W	3/14/2010	44.0	2000	12.12	2.530	28.050	11.09
LSETT	W	3/14/2010	44.0	3080	74.69	2.150	25.420	11.82
LSETB	W	3/14/2010	44.0	1402	25.94	1.400	14.040	10.03
USDTT	W	3/14/2010	44.0	1856	30.84	1.590	18.990	11.94
USDTB	W	3/14/2010	44.0	2123	22.67	2.330	20.920	8.98
USANT	W	3/14/2010	44.0	300	8.77	0.970	10.730	11.06
USATB	W	3/14/2010	44.0	3160	42.38	1.430	17.870	12.50
USCTB	W	3/14/2010	44.0	1500	66.60	1.520	16.780	11.04
LSETT	S	7/25/2010	7.6	575	3.76	7.140	68.780	9.63
LSFNT	S	7/25/2010	7.6	175	3.27	3.110	35.530	11.42
USDTT	S	7/26/2010	1.8	230	1.00	1.660	17.390	10.48
USDTB	S	7/30/2010	12.0	2025	17.03	1.910	21.460	11.24
LSFTB	S	7/30/2010	12.0	1915	33.10	2.760	25.980	9.41
LSFNT	S	7/30/2010	12.0	2980	12.36	3.650	37.510	10.28
LSFTT	S	7/30/2010	12.0	3020	33.01	1.590	18.290	11.50

Runoff Collection Unit	Seas.	Runoff Event Date	Event Rainfall Total (mm)	Runoff Volume (ml)	Sediment (g)	Total Nitrogen (g/kg-1)	Total Carbon (g/kg-1)	C/N
LSETT	S	7/30/2010	12.0	3180	32.69	2.770	34.600	12.49
USCTT	S	7/30/2010	12.0	685	9.29	1.940	19.720	10.16
USDTT	S	7/30/2010	12.0	545	8.26	1.160	13.180	11.36
USATB	S	7/30/2010	12.0	2925	16.63	1.880	19.750	10.51
USATT	S	7/30/2010	12.0	810	15.17	1.260	14.910	11.83
USBTB	S	7/30/2010	12.0	2055	15.80	1.970	21.780	11.06
USBTT	S	7/30/2010	12.0	490	3.75	1.050	10.980	10.46
USATB	S	8/18/2010	19.6	3080	55.65	1.860	21.890	11.77
USANT	S	8/18/2010	19.6	300	8.40	1.410	14.630	10.38
USBTT	S	8/18/2010	19.6	3370	51.77	1.350	14.550	10.78
USBTB	S	8/18/2010	19.6	2965	66.93	1.370	15.820	11.55
USBNT	S	8/18/2010	19.6	900	28.83	0.895	9.175	10.25
USCTB	S	8/18/2010	19.6	2530	26.50	1.680	18.920	11.26
USDTT	S	8/18/2010	19.6	235	9.44	0.950	10.255	10.79
USDTB	S	8/18/2010	19.6	1875	16.83	2.280	26.790	11.75
USDNT	S	8/18/2010	19.6	590	10.47	1.950	22.690	11.64
LSETT	S	8/18/2010	19.6	2895	76.30	2.160	25.360	11.74
LSFNT	S	8/18/2010	19.6	3450	15.22	3.190	39.770	12.47
USCNT	S	8/18/2010	19.6	240	4.85	2.680	34.690	12.94
USCTT	S	8/18/2010	19.6	2840	32.86	1.890	17.890	9.47
USDTT	S	9/22/2010	11.0	3000	35.86	1.840	18.410	10.01
USDTB	S	9/22/2010	11.0	2550	14.47	1.170	12.510	10.69
USDNT	S	9/22/2010	11.0	170	2.88	3.020	39.880	13.21
USBTB	S	9/22/2010	11.0	915	11.86	1.660	19.330	11.64
USBNT	S	9/22/2010	11.0	170	7.99	1.140	12.620	11.07
USATB	S	9/22/2010	11.0	3130	37.31	1.730	19.830	11.46
USBTT	S	9/22/2010	11.0	2130	26.71	1.490	16.120	10.82
USATT	S	9/22/2010	11.0	2405	30.93	1.560	18.170	11.65
USCTB	S	9/22/2010	11.0	1640	16.13	2.280	26.820	11.76
USCNT	S	9/22/2010	11.0	210	6.04	3.615	35.750	9.89
LSFTB	S	9/22/2010	11.0	1610	24.69	1.850	20.000	10.81
LSFTT	S	9/22/2010	11.0	1010	10.68	1.900	25.590	13.47
LSENT	S	9/22/2010	11.0	210	1.63	3.960	45.740	11.55
USBTT	S	10/5/2010	3.8	120	2.94	7.735	37.760	4.88
USDTB	S	10/5/2010	3.8	120	2.04	9.000	56.330	6.01
USCNT	S	10/7/2010	35.4	na	53.90	1.650	20.410	12.37
USDNT	S	10/7/2010	35.4	1450	21.08	2.180	30.550	14.01

Runoff Collection Unit	Seas.	Runoff Event Date	Event Rainfall Total (mm)	Runoff Volume (ml)	Sediment (g)	Total Nitrogen (g/kg-1)	Total Carbon (g/kg-1)	C/N
USDTT	S	10/7/2010	35.4	3660	124.11	1.480	16.940	11.45
USCTB	S	10/7/2010	35.4	3550	107.81	1.840	20.730	11.27
USBTB	S	10/7/2010	35.4	3190	70.07	1.730	19.480	11.26
USCTT	S	10/7/2010	35.4	2750	86.22	1.840	21.410	11.64
USATB	S	10/7/2010	35.4	3110	154.66	1.530	18.310	11.97
USANT	S	10/7/2010	35.4	405	24.87	2.060	28.450	13.81
LSETT	S	10/7/2010	35.4	2890	217.53	2.790	34.980	12.54
LSENT	S	10/7/2010	35.4	3215	35.46	2.890	36.390	12.59
LSFNT	S	10/7/2010	35.4	2590	20.75	2.850	36.660	12.86
USBNT	S	10/7/2010	35.4	490	28.28	1.150	12.410	10.79

Table D.2. Soil organic matter of runoff samples, Winter (n=12) and Summer (n=26).

Runoff Collection Unit*	Runoff Event Date	SOM (%)
Upper TT	3/14/2010	4.93
USDNT	3/14/2010	5.37
LSFTT	3/14/2010	3.78
LSFTT	8/18/2010	4.64
LSFTB	3/14/2010	6.00
USCTB	3/14/2010	6.70
USDTT	3/14/2010	5.84
LSETT	8/18/2010	11.16
USBTB	8/18/2010	5.42
Non-terrace (upper and lower)	8/18/2010	7.62
Upper TB	8/18/2010	6.80
USDTB	8/18/2010	6.24
USCTT	8/18/2010	7.00
USDTT	10/7/2010	6.04
USCTB	10/7/2010	5.69
USBTB	10/7/2010	5.91
USCTT	10/7/2010	6.90
USATB	10/7/2010	5.94
LSETT	10/7/2010	8.77
LSENT	10/7/2010	12.76
USDNT	10/7/2010	8.10
USANT	10/7/2010	6.03
USBNT	10/7/2010	4.76

Runoff Collection Unit*	Runoff Event Date	SOM (%)
LSFTT	10/7/2010	4.63
USATT	10/7/2010	4.63
Upper TB	9/22/2010	6.98
Upper TB	9/22/2010	6.49
Uppter TT	9/22/2010	5.58
Uppter TT	9/22/2010	5.22
USATB	7/30/2010	6.35
LSFTB	7/30/2010	6.72
LSFNT	7/30/2010	8.51
Terraces Upper	2/10/10 and 1/31/10	6.57
Terraces Upper	2/10/10 and 1/31/10	6.59
Non-terrace (upper and lower)	1/20/10 and 3/2/10	7.14
USDTT	1/31/2010	5.01
USCTT	1/31/2010	5.70
USCNT	1/31/2010	6.03

*Samples were aggregated.