Anthropogenic influences on American Indian agricultural soils of the Southwestern United States

by

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Here, I focus on some of the individuals who played particularly crucial roles in my career and training. My first real exposure to soils came from several years of work as a field archaeologist in many parts of the U. S. during the late 70s and early 80s. I became increasingly intrigued by the relevance and implications of soil morphology and genesis for interpreting archaeological deposits, so I returned to school for graduate training in archaeology and pedology at Louisiana State University. There, I had the good fortune of studying under the eminent soil scientist, Dr. Bob Miller. He served on my Master's committee before his untimely death in 1987. I have many happy memories of my time in the field, lab, and classroom with Dr. Miller, and I credit him for further sparking my interest in soil science.

Dr. Jon Sandor played a vital role in helping me return to school for doctoral training in soil science, serving as my major professor at Iowa State University. I first met Jon almost 10 years ago, shortly after learning of his research on soil fertility and productivity of ancient agricultural soils in the Mimbres area of New Mexico. He invited me for field visits to the

Zuni Indian Reservation in his first two field seasons on the reservation (1991 and 1993). We collaborated on a soil study of rock mulch fields in central Arizona between 1992 and 1996, after which he offered me an NSF-funded research assistantship to work on my doctorate on Zuni agricultural soils. Jon also helped me obtain the first Miller Fellowship in ISU's Agronomy Department, which helped clinch my decision to return to school. In the field he taught me some of his many *tricks* for describing soil profiles and interpreting the genesis of soil stratigraphy. Both before and during my studies at ISU, Jon always treated me as his peer and friend. He ensured my freedom to pursue doctoral research on topics of my choosing, provided advice and a guiding hand as needed, but never tried to impose his ideas on me. I will always be indebted to Jon for his help and encouragement to obtain my doctorate.

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ABSTRACT

This study focused on determining and assessing anthropogenic influences on soil quality in two American Indian agricultural systems of the Southwest U. S. One is a runoff system in the Zuni area of New Mexico where runoff farming has been practiced for over two millennia, and the other is an ancient rock mulch system in southeast Arizona that was abandoned over 500 years ago. Results of the Zuni study indicate that cultivation has had both positive and negative effects on soil productivity. Relative to uncultivated soils, cultivated soils tend to have slightly elevated bulk density and pH levels, and inconsistent changes in N and organic C. Soil changes at the levels found are not sufficient to indicate that cultivation caused degradation. Potential negative impacts are offset to varying degrees by thickened topsoils, co-sedimentation of organic matter and silt in fields, and organic matter coatings on peds.

Extensive rock mulch features (grids, terraces, and rock piles) were built to conserve water and nutrients in the shallow rooting zone of the Safford fields of Arizona. Compared to uncultivated soils, mulched soils have elevated C, N, and available P concentrations and no evidence of soil compaction. Existing vegetation concentrated in the rock mulch features today demonstrates their effectiveness in conserving moisture and nutrients. There is no evidence that ancient rock mulch farming in Arizona caused soil degradation, and it appears that agricultural practices actually improved soil quality for crop production.

An ancillary study was undertaken to measure soil changes caused by the western harvester ant (*Pogonomyrmex occidentalis*). This research aimed to determine their effect on

soil productivity in the context of agricultural land use and landscape modifications. Results indicate that ant-affected soils have elevated levels of organic C, N, and available and total P, so they have a positive influence on agricultural soils. In addition to nutrient enrichment, ants help to aerate the soil and increase its hydraulic conductivity and water-holding capacity. Ant effects on surface soils extend to entire landscapes within about 2500 years, which is within the time frame of agricultural practices in the Zuni area.

CHAPTER 1
INTRODUCTION

This thesis focuses on how humans and ants influence soil physical and chemical soil properties. Soil morphology, genesis, and productivity are strongly influenced by biological factors, including humans, microbes, plants, and fauna. Despite the crucial role played by the biotic factor in pedogenesis, it is probably the least studied of the soil-forming factors. Anthropogenic influences on agriculture are increasingly being studied today, however, because of their importance in evaluations of agricultural sustainability. I conducted three separate studies for my dissertation research, two studies on American Indian agricultural systems in the Southwest United States and one on the interaction of ants, plants, and soils.

The agricultural soil studies consist of a traditional runoff farming system in western New Mexico on the Zuni Indian Reservation, and an ancient agricultural complex of rock mulch features and terraces located near Safford, Arizona, in the southeast part of the state. The principal objective of the Zuni soil study is to test the hypothesis that long-term cultivation has altered, but not seriously degraded agricultural soils. Both the Zuni and Safford studies were aimed at documenting soil properties and assessing soil productivity. The Zuni agricultural soils are among the oldest, more or less continuously farmed soils in the United States, at over two millennia, and the Safford gridded fields are unrivaled in extent and complexity in the Southwest. Agricultural soils in arid and semiarid lands, both ancient and modern, are well suited to agronomic study, because pedogenesis proceeds more slowly than in humid regions, so we have a greater chance of detecting many anthropogenic influences on soil properties.

Overcoming low water availability is usually viewed as the major hurdle in achieving agricultural sustainability in deserts of the Southwest. This situation contrasts sharply with humid regions, where soil fertility maintenance is usually the main limiting factor. Nitrogen deficiency, however, is common in desert soils, and its effect in limiting agricultural production can be nearly as great as water availability. This is especially true for cropping systems dependent on maize, which commonly depletes soil nitrogen. Some soil studies in the Southwest indicate that ancient farming systems degraded the nutrient status of agricultural soils but other studies have found that soil fertility was probably not seriously degraded, and in some cases may have even been improved, by cultivation.

The few soil studies of American Indian farming systems that have been conducted in the Southwest indicate that the consequences of prehistoric cultivation in terms of soil productivity are highly variable, due to many interacting environmental and cultural factors such as climate, topography, hydrology, soil type, native vegetation, crop type and variety, agricultural technology, and duration and intensity of cultivation. The two studies of traditional and ancient agriculture presented here contribute to a small but growing body of literature on this topic. This literature is reviewed in greater detail in Chapters 2 and 3.

There are a number of similarities and differences between the two farming systems. In drawing these comparisons and contrasts, however, it is important to keep in mind that other types of farming systems were simultaneously practiced in both study areas, including irrigation. Indeed, an important hallmark of Native American farming systems in the Southwest is the use of diverse soils, landscapes, and management practices to counter the vagaries of drought and flooding. The most obvious difference between the two systems being compared here is the greater temporal continuity in Native American farming at Zuni, where agriculture has been practiced for over two millennia. The Safford system is an ancient system that has probably been abandoned for over 500 years, and there are no modern analogues for the type of rock mulch agriculture that was practiced there.

Both field systems are located in semiarid environments and both rely on capturing runoff water to supplement direct rainfall. The Zuni fields are situated at about 1200 m higher elevation than the Safford Basin, so snowmelt is an important source of moisture in the early growing season at Zuni. The Zuni area receives about 50% more precipitation than the average of about 200 mm that fall in the Safford Basin. In addition, because of the cooler climate of the Zuni area, precipitation is less subject to evaporation, so effective moisture for crop production is much higher than in the Safford Basin. Consequently, maize agriculture is a viable option at Zuni and not in the thinner, droughty soils of the Safford fields.

Because of the hotter and drier climate of the Safford Basin, the farmers took advantage of cobbly alluvial fans to build the extensive gridded fields and other types of agricultural rock features (e.g., rock piles and rock alignments to create agricultural terraces). This type of rock mulch agriculture was not practiced at Zuni, or at least not nearly to the extent as at Safford. Extensive rock mulching was used to conserve water and nutrients in the shallow rooting zone above a petrocalcic horizon in the Safford fields. In contrast, the Zuni farmers relied mainly on shallow argillic horizons to slow infiltration and hold moisture in the rooting zone.

The Zuni system takes advantage of organic-rich sediments carried by runoff water to naturally fertilize their fields. The agricultural fields at Zuni keyed into small watersheds for establishing their fields, but the catchment areas used by the fields are actually much larger than those of the Safford fields. The Safford fields were built on an elevated fan terrace that is deeply dissected, and thus the grid features are largely bypassed by runoff. The grid features themselves, however, appear to function as micro-catchments for highly drought-tolerant crops. The actual crop(s) grown is unknown at present, but pollen and macrobotanical analysis of archaeological features is now underway in an attempt to determine what was grown. At present, it seems that agave or other higher drought-tolerant plants were cultivated.

In addition to the two studies of agricultural soils, an ancillary study was undertaken to investigate the magnitude of soil changes caused by activities of an earth-dwelling species of ant, the western harvester ant (*Pogonomyrmex occidentalis*). This study was conceived after observing numerous ant mounds in Zuni fields, suggesting that ants are a particularly important biological factor in soil formation in this environment. The western harvester (*Pogonomyrmex occidentalis*) and other closely related harvester ants (*P. barbatus*, *P. maricopa*, *P. Oweeyi*, and *P. rugosus*) are widespread in grasslands, deserts, and woodlands of the western U. S. The ant study was conducted to distinguish their effects in different agricultural contexts in conjunction with the Zuni soil study. This study of the influence of ants on soil properties focused on comparing their effect on soils in different agricultural contexts (uncultivated, fallow, and cultivated fields). Analyses made at pedon and microscopic scales are related to the broader landscape through observations of ant colonies and previous studies of the age of western harvester colonies.

The ant study focuses on six research questions: (1) What chemical and physical soil properties are influenced by harvester ants in a semiarid, uncultivated field dominated by sagebrush, and how do they affect soil fertility? (2) What micromorphological properties are associated with ant-affected soils? (3) How do colony spacing, mound and clearing properties, and vegetation associations vary between colonies in uncultivated, fallow, and cultivated fields? (4) How does the rate of soil turnover vary between colonies in uncultivated, fallow, and cultivated fields? (5) How long does it take for the entire landscape to become affected by ant activity? (6) How do soils, plants, and ant colonies influence one another, and what are some of the major interactions between them?

Dissertation Organization

This dissertation is organized into five chapters. Following the introductory chapter are three chapters constituting the main body of work of my dissertation. Chapters 2, 3, and 4 are all written as manuscripts to be submitted for publication. Literature reviews are contained in each manuscript, so I did not include one as a chapter in this thesis. This was done because the studies are so different from one another, so it was not logical to integrate a literature review as a single chapter.

Chapter 2 reports on the findings of our study of the Safford gridded agricultural fields. A previous draft of this manuscript, co-authored with my major professor, Dr. Jonathan A. Sandor, and Dr. Dale R. Lightfoot (Professor of Geography, Oklahoma State University), has already been submitted to the co-Principal Investigators. Dr. Lightfoot's contribution to this chapter is the sections on granulometry and soil moisture tests, and I edited his sections and incorporated them into the text at the request of the co-PI's of the Safford project, Dr. William E. Doolittle (Professor of Geography) and Dr. James A. Neely (Professor of Anthropology), both of the University of Texas at Austin. Drs. Doolittle and Neely are compiling and editing manuscripts from all members of the research team, which includes archaeologists, cultural and physical geographers, ethnobotanists, and soil scientists. Within the year they intend to submit this edited volume (which is yet to be titled) to University of Arizona Press for publication. The U of A press has already expressed an interest in publishing a book on the Safford project in their *Anthropological Papers* series.

Chapter 3 presents the results of the NSF-funded Zuni soil study. This manuscript is a detailed scientific investigation of runoff agriculture and the long-term influences of cultivation. I co-authored this paper with Dr. Jonathan A. Sandor and Jay Norton. Dr. Sandor completed the field sampling and analysis in 1991 at one of the three paired cultivated and uncultivated fields (the Sanchez field), and he permitted Norton to integrate his data into his Master's research on the watershed of the Sanchez field. Norton contributed to this manuscript by allowing me to integrate soil data from his Master's research on the Sanchez field with the two other paired fields investigated as part of the NSF project. Mr. Norton also played a crucial role in the NSF project, serving as Project Coordinator. We intend to submit this manuscript to the Journal of Arid Environments for publication. Other manuscripts on our Zuni soil study are being prepared for publication, but these results are not presented in my dissertation.

Chapter 4 presents the results of our study of western harvester ant interactions with soils and vegetation. The major focus of this study is on soil formation and productivity, and the long-term impacts of ants on the landscape. I co-authored this chapter with Dr. Jonathan A. Sandor, and we intend to submit it to *Pedobiologia* for publication.

Chapter 5 presents an overview of major conclusions of my dissertation. Sections with more detailed conclusions are presented at the end of Chapters 2-4 for the three respective studies. A brief synthetic discussion is included in Chapter 5 that is not provided elsewhere.

Appendix A is a compilation of soil profile descriptions and classifications for the Zuni, Safford, and ant studies. Appendix B provides all of the raw soil data for the Zuni soil study. Appendix C presents photocopies of sketch maps prepared in the field to show soil sampling locations for all extensive (or unpaired) fields sampled in the Zuni soil study. These sketch maps also depict topographic information and other observations deemed noteworthy.

CHAPTER 2
SOIL INVESTIGATIONS AT A LATE PREHISTORIC AGRICULTURAL COMPLEX IN THE SAFFORD BASIN

Manuscript submitted to editors for book to be published by the University of Arizona Press

Jeffrey A. Homburg, Jonathan A. Sandor, and Dale R. Lightfoot)

ABSTRACT

Soil properties associated with gridded rock alignments, rock piles, and terraces were evaluated as part of an interdisciplinary study of a late prehistoric agricultural complex. Research was aimed at documenting soil properties and assessing agricultural productivity. This study area is located in southeast Arizona, on the distal end of an alluvial fan terrace overlooking the Gila River. Soils consist chiefly of gravelly loams and clay loams dominated by shallow petrocalcic or argillic horizons, both of which impede water infiltration and hold moisture in the rooting zone. Compared to uncultivated soils, which tend to be moderately alkaline (ca. pH 8.1-8.4), agricultural soils are commonly slightly alkaline (ca. 7.7-8.0). Reduced pHs at these levels are beneficial for crop production due to increased plant availability of most nutrients. C, N, and available P concentrations are notably higher in the soils of grid and terrace alignments, and upper terrace positions. No consistent bulk density trends were found, so there is no indication that ancient cultivation practices caused appreciable soil compaction. Soil analyses suggest that rock mulch features (grid alignments, terrace alignments, and rock piles) and terrace positions immediately below the alignments are the most productive agricultural contexts. It is noteworthy that the upper and lower terrace positions near the alignments are where existing vegetation, mainly creosotebush, is

concentrated today. It is possible that the lower soil productivity of grid interiors is caused at least in part by cultivation, but is seems more likely that rock clearings within grids acted to facilitate runoff to grid alignments downslope. Soil nutrient levels are sufficient to support maize agriculture, but thin rooting zones, high temperatures, low rainfall, and low runoff throughout most landscape positions of the field suggest that drought-tolerant crops such as agave were cultivated.

INTRODUCTION

This study presents the results of a soil investigation focused on a prehistoric agricultural complex in the Safford Basin. The Safford Basin is located in the upper Gila River valley of southeast Arizona, sandwiched between the Pinaleno Mountains to the south and the Gila Mountains to the north. Primary agricultural land in the Safford Basin is concentrated on the floodplain and lower alluvial terraces of the Gila River and flanks of major tributaries draining the northern Pinaleno Mountains. These geomorphic settings are well suited for irrigation and floodwater farming. Runoff and dryland fields containing gridded rock alignments, agricultural terraces, and rock piles, such as those examined by this investigation, were commonly built on cobbly, alluvial fan terraces overlooking the Gila River valley.

The Safford Gridded Fields (SGF), an agricultural complex of agricultural rock mulch features and terraces, is the focus of this soil study. Though rarely as elaborate as those of the SGF, prehistoric rock mulch features have been identified in cobbly landscapes throughout the Southwest by many archaeological surveys. In a few places in the Hohokam, Sinagua, and Anasazi culture areas, farmers applied gravel and cobbles across planting surfaces as a way to reduce soil erosion by wind and water, increase soil temperature to extend the growing season, increase water infiltration, and reduce evaporative loss of water from wind and sun. Examples of mulch agriculture in the Southwest include use of rock piles in southern Arizona (Fish et al. 1992, Fish et al. 1985, Masse 1979) and central Arizona (Homburg 1997, Homburg and Sandor 1997), ash and cinder ridges and mounds in the Sinagua region of northern Arizona (Berlin, et al. 1990), Hopi sand dune cultivation in northeast Arizona (Doolittle 1998, Forde 1931, Hack 1942), and pebble or gravel mulch gardens around Anasazi Pueblo sites in northern New Mexico (Lang 1981, Lightfoot 1993a, Lightfoot 1993b, Lightfoot 1994, Lightfoot and Eddy 1995, Maxwell and Anschuetz 1992, Ware and Mensel 1992). Most of these latter features were constructed across the tops of extensive terraces, in a landscape context almost identical to the SGF.

The SGF is situated on the T3 fan terrace (Gelderman 1970: Fig. 6). The T3 terrace, the second youngest terrace in the Safford Basin, is situated about 20 m above the floodplain at a minimum. Brenda Hauser, geologist with the U.S. Geological Survey in Tucson, has completed more detailed geomorphic mapping of the study area but the results are not yet published. The T3 terrace is poorly dated, but the stage of soil development suggests it is roughly 100,000 to 200,000 years old at minimum. It is noteworthy that the T3 terrace along this reach of the Gila River has been tectonically uplifted and tilted. Several southeast-trending faults cross the SGF, and faulting has isolated this terrace segment from the rest of the T3 terrace. Consequently, the size of watershed of the SGF has been reduced, which has altered the hydrology to significantly reduce stream dissection compared to other fan terrace segments (Hauser 1999, personal communication, January 29). Reduced stream dissection was probably an important consideration for the ancient farmers who selected this particular area for building the SGF.

The most striking agricultural features at the SGF are clearly the grid alignments, which are impressive because of their elaborate layout and large size, with fields spread over a 2.4 by 1.6-km area. Rock mulch features of the SGF cover about 822,000 m^2, which is much more extensive than the rock mulch fields of northern New Mexico; including the pebble-mulched fields of the Galisteo Basin, which collectively cover 41,000 m^2, and the gravel-mulched fields of the Chama-Ojo that cover at least 70,000 m^2 (Cordell 1998, Lightfoot 1993a, Lightfoot 1993b, Lightfoot and Eddy 1995, Maxwell and Anschuetz 1992, Ware and Mensel 1992). Rock mulch techniques have been documented in ancient or historic times in Israel, Italy, Peru, Argentina, New Zealand, Canary Islands, and China across areas approaching or exceeding the area covered by the rock mulch features of the SGF (Lightfoot 1994, Lightfoot 1996). In every case of rock mulch from the Southwest and elsewhere, the method was used only in places with a growing season moisture deficit.

The extent and complexity of the grid features of the SGF are unrivaled in the Southwest. Even world-wide, the only fields resembling the SGF that we are aware of are the Engaruka fields in the Rift Valley of East Africa, which were abandoned in the 1700s (Sutton 1969, Sutton 1978, Sutton 1990). There is one major difference between the SGF and the Engaruka fields; however, the latter are watered by runoff irrigation fed by perennial and ephemeral drainages and no such drainage exists at the SGF. Compared to the Engaruka fields, as well as many other fields in the Southwest, the SGF are situated in such a harsh, arid environment for agriculture, which makes it especially puzzling why the farmers went to so much effort to build such an elaborate network of agricultural features in this location. The SGF stand in stark contrast to the nearby highly productive, irrigated cotton fields on the Gila River floodplain today.

Because of their thin, droughty soils, food from upland fields such as the SGF likely served an important but supplementary role in the diet of ancient farmers of the Safford Basin. Yet there are advantages to farming upland fields. The elevated position of the fan terraces on the valley margin of the Gila River valley is advantageous for avoiding or minimizing killing frosts caused by cold air drainage. Upland settings often have another important advantage for agricultural production; they usually have subsurface horizons that impede and conserve moisture in the rooting zone (e.g., clay-enriched zones known as argillic horizons, carbonate-plugged horizons known as petrocalcic horizons; the latter are commonly referred to as *caliche*), and this situation is certainly true at the SGF. Although upland soils enjoy certain agricultural advantages, there are also disadvantages. Namely, upland soils are generally thinner, contain more rock fragments, and are more drought-prone than the alluvial bottomlands. Because of great variability in the length of the growing season and unpredictable floods, combined with highly unpredictable precipitation patterns both spatially and temporally, ancient farmers commonly spread fields over different soils and landforms as a buffering strategy for ensuring adequate food supplies. Such agricultural diversity is a hallmark of agricultural systems in the Southwest as a way to minimize the risk of crop failure (Woosely 1980). Many types of prehistoric agricultural systems have been documented in the greater Southwest (Ciolek-Torrello and Welch 1994, Doolittle 1988, Fish

1995, Fish and Fish 1984, Homburg 1997, Lightfoot 1990, Rankin and Katzer 1989, Toll 1995, Vanderpot 1992, Woodbury 1961) and elsewhere in the world (Evenari et al. 1982, Sutton 1990).

Overcoming low water availability is usually viewed as the major hurdle in achieving agricultural sustainability in arid and semiarid lands of the Southwest, and that is clearly the case for the drought-prone soils of the SGF. This situation contrasts sharply with the humid Mesoamerican lowlands, where soil fertility maintenance is the main limiting factor (Dregne 1963: 219, Sanders 1992: 283). Still, soil fertility is an important concern in the Southwest, and it is an error to think that productivity is limited by water alone (Ludwig 1987). Nitrogen deficiencies, in fact, are so common in desert soils that its effect in limiting agricultural production is almost as great as water availability (Nabhan 1983, 1984, Rommey et al. 1978; Sandor and Gersper 1988). And cultivation, especially of highly consumptive crops such as maize, heightens this problem by rapidly depleting already low nitrogen levels (Doolittle 1984: 257, Loomis and Connor 1992: Fig. 12.1, Stevenson 1982).

Ancient agricultural soils of upland (or non-riverine) fields in arid and semiarid regions of Arizona are well suited for agronomic research for at least four reasons: (1) soil formation processes (e.g., weathering, leaching, and illuviation) proceed much more slowly in deserts than in humid environments, so soil changes caused by ancient cultivation practices tend to persist and be detectable over the last millennium at a minimum; (2) most ancient fields have not been cultivated since they were abandoned, so historic farming practices such as plowing and artificial fertilizer applications have not masked or erased soil properties reflecting prehistoric farming; (3) upland landforms, including alluvial fan and river terraces, are often geomorphically stable, so ancient agricultural soils associated with them are readily accessible for study; and (4) the presence or absence of agricultural facilities (rock alignments, rock piles, and terraces) provide important clues for discerning and collecting cultivated and uncultivated soil samples.

Some soil studies in the Southwest have found that ancient farming systems degraded the nutrient status of agricultural soils. For example, long-term cultivation significantly lowered the fertility of terraced fields in the Mimbres area (Sandor 1983), and farming practices at prehistoric fields near Flagstaff, Santa Fe, and at Mesa Verde tended to lower phosphate and soil fertility levels severely enough to cause fields to become unproductive and abandoned (Arrhenius 1963). Other studies in central Arizona have been conducted in settings similar to the Safford Basin gridded fields, and these studies have found that soil fertility was probably not seriously degraded by cultivation (Homburg 1994, Homburg and Sandor 1997). The few soil studies conducted thus far in the Southwest indicate that the consequences of prehistoric cultivation in terms of soil productivity are highly variable, due to many interacting environmental and cultural factors such as climate, topography, hydrology, soil type, native vegetation, crop type and variety, agricultural technology, and duration and intensity of cultivation.

In Sandor's study of the long-term effects of cultivation in the Sapillo and Mimbres valleys of southwestern New Mexico, Mimbres agricultural terrace soils associated with small rock alignments were compared to uncultivated control samples (Sandor 1983, Sandor et al. 1986, Sandor et al. 1990). Results indicated that the primary anthropogenic soil changes were degradational, and that the effects of cultivation could be detected about 800 years after the fields were abandoned. In comparison to uncultivated soils, Sandor found that cultivated soils were lighter in color, more compacted, and had thicker A horizons with more blocky and less granular structural aggregates. In addition, he found that cultivated soils had lower organic carbon, nitrogen, total and available phosphorus, and copper levels, and higher manganese and pH values. Rock alignments primarily functioned as dams to reduce the velocity of runoff, increase infiltration, and thicken naturally thin A horizons by impounding sediments (Sandor, et al. 1986). Through the use of different fertilizer treatments, a controlled greenhouse experiment was used to compare the growth of chapalote, a primitive variety of maize, and barley in terrace and uncultivated soils (Sandor 1983, Sandor and Gersper 1988). Sandor found that both plants were dramatically stunted in the terrace soils, and that nitrogen is the most limiting nutrient for plant growth. Terraced soils were found to be fairly productive if fertilized with nitrogen and to some extent, phosphorus.

The findings of Sandor's Mimbres study contrasts strongly with that of two soil studies in Arizona, one in the Tonto Basin (Homburg 1994) and the other in the Horseshoe Basin (Homburg and Sandor 1997). Both studies were conducted in low desert settings comparable to the Safford Basin in elevation and temperature, but the Tonto and Horseshoe basins receive about 50 percent more annual rainfall than the Safford Basin, which averages about 24 cm (or about 9.5 inches; Sellers and Hill 1974: 266, 383, and 412). The Horseshoe Basin and Tonto Basin studies focused on measuring the effects of cultivation on soil fertility by comparing rock pile and rock alignment soils with adjacent uncultivated soils. Agricultural soils in both study areas generally had similar or elevated levels of nitrogen, phosphorus, and organic carbon, often at levels of statistical significance, and no evidence of compaction was noted in the cultivated soils. The increased fertility levels of the agricultural soils are associated with the effects of rock mulching, but it is uncertain if these changes occurred during or after the time the fields were cultivated. Importantly, the lack of indications of decline in soil fertility in these cases may be due to the combined effects of many factors, including short-term use of fields, replenishment of nutrients in organic debris deposited naturally, use of rock mulch to reduce organic matter oxidation, cultivation of drought-adapted crops that have low nutrient requirements (e.g., succulents such as agave), and nutrient recovery resulting from natural, post-cultivation litter additions. It is possible that other desert plants were cultivated, such as yucca, prickly pear, or some other type of cactus.

The SGF provides an important opportunity for documenting soil properties and evaluating cultivation effects in a part of the Southwest and in a type of field system that has received little archaeological attention to date. The large size of the fields, presence of three distinct field systems (rock grids, rock piles, and terraces; Figures 2.1-2.2), and widespread cultural features and artifacts associated with agricultural use and processing activities (e.g., masonry field houses, roasting pits, upright stone field markers, and lithic tools such as tabular knives and large primary flakes) are clear indications of intensive field use, probably over one or two centuries at a minimum. Charred agave remains recovered from roasting pits exposed in the Peck Wash alluvium below Locality 1 yielded uncorrected radiocarbon dates of AD 500 ±50 and AD 1340 ±50, thus providing important, though indirect, clues of a potential cultivar and the timing of cultivation at the SGF. One or both dates may be from

Figure 2.1. Rock alignment grids and grid interiors.

Figure 2.2. Agricultural terraces and rock alignments.

agave that was not cultivated. It is important to note, however, that the latter date is consistent with the age of masonry field houses and pottery found at the SGF, as well as the timing of agave cultivation documented elsewhere in southern and central Arizona, including the northern Tucson Basin and the Horseshoe Basin.

This SGF soil study aims to measure the effects of cultivation on soil fertility and to assess the agricultural suitability of the soils on the alluvial fan terrace. We will use soil data to help elucidate why the SGF were built where they were and speculate about what crops may have been the cultivated. Soil profile descriptions and a suite of physical and chemical laboratory tests were used to characterize the fertility and soil morphological properties important for water-holding properties of the soil.

METHODS

Soil samples were collected during a one-week period, March 7-11, 1997. Soil sampling focused on a variety of agricultural features in the westernmost locus of the field, west of Peck Wash and immediately north of the Graham Canal at the northern edge of the Gila River floodplain. This area, designated Locality 1, was chosen for soil sampling because of its easy access and because a wide range of agricultural feature types are present, including grid alignments, rock piles, and terraces. Soil sampling was confined to Bureau of Land Management (BLM) property, which encompasses most of Locality 1.

In all, 49 soil samples were collected for analysis, 40 from 15-cm-deep shovel pits (SP) placed in agricultural features and nearby uncultivated controls, and nine from two different soil profiles. Soil sampling concentrated on the grid features; two gridded rock alignments and adjacent grid interiors were sampled from each of four landscape positions of Locality 1, for a total of 16 samples. Six control samples for the grid features were collected (SP 27-32) from soils and landscape positions similar to the cultivated areas, including three control samples from both the southeastern and northern sectors of Locality 1. The grid features were so extensive that it was difficult to find controls areas that were perfectly matched to the cultivated soils; nevertheless, the control areas chosen appeared similar enough to make the comparisons valid. Three rock piles were sampled, along with control samples from next to each rock pile. A trench (T 1) and 6 SP's were excavated to sample the agricultural terraces located on the prominent east-facing escarpment in the southern part of Locality 1. In all, nine samples were collected from terrace contexts, including three samples from terrace rock alignments and three from the terrace positions located immediately above and below each alignment sampled. Three control samples for the terrace samples were collected from the escarpment east of Locality 1 and Peck Wash, an area with a comparable slope to that of the terraces. Deeper soil profile samples were obtained next to two historic prospector's pits (PP), including a grid interior in the profile of PP 1 in the central part of Locality 1 and from a trench (T 2) excavated between PP 2 and a rock pile in the northern part of Locality 1. Soil profiles were described, which entailed identifying soil horizons, recording morphological properties such as depth, color, texture, structure, and consistence, and classifying pedons classified using Soil Taxonomy (Soil Survey Staff 1993, Soil Survey Staff 1998).

Selection of particular soil analyses was based mainly on results obtained by previous studies in Arizona (Homburg 1994, Homburg and Sandor 1997) and New Mexico (Sandor

1983), with tests focusing on properties that tend to reflect long-term stability. Particle-size and bulk density analyses were conducted to obtain data on soil texture, moisture and nutrient retention, and compaction. Bulk density analysis was completed for all samples but those that were too weakly aggregated to complete the test. Chemical analyses included determinations of pH, organic and inorganic carbon, nitrogen, total and available phosphorus, and calcium carbonate equivalent. Particle-size, bulk density, and pH analyses were completed in soil labs at Iowa State University, and the organic carbon, total nitrogen, and total and available phosphorus analyses were conducted at the University of Montana, under the supervision of Jay Norton. Calcium carbonate equivalent analysis was conducted by Louis Moran at Iowa State University. Subsamples for each laboratory test were taken from bulk samples collected in the field. Initial sample preparation involved air-drying and sifting samples through a 2-mm sieve to remove gravel, roots, and other coarse undecomposed organic debris. Determinations of total carbon, nitrogen, and phosphorus analyses were done on ten-gram subsamples that were mechanically ground fine enough to pass through a No. 100 sieve.

Particle-size distributions were determined using the sieve and pipette method (Gee and Bauder 1986: Method 5.4), with carbonates included. Soil samples were pretreated with a 30 percent hydrogen peroxide reagent for organic matter digestion, hydrochloric acid to remove carbonates, and a sodium hexametaphosphate solution for clay dispersion. Bulk density analysis was measured using the clod method, using paraffin-coated peds (Blake and Hartge 1986: Method 13.4). Bulk density samples were analyzed in duplicate and averaged, and if the coefficient of variation exceeded 5%, a third sample was analyzed and averaged with the others. After peds were weighed in water, gravel was removed and weighed, so the bulk density of the <2 mm fraction could be determined. Soil pH was measured in a 1:1 suspension (weight basis) of soil and distilled water using a glass electrode (McLean 1982). Total carbon and nitrogen concentrations were determined using a Leco CHN analyzer, and inorganic carbon was measured by titrimetry (National Soil Survey Center 1996). Total phosphorus concentrations were determined using an alkaline oxidation extract (Dick and Tabatabai 1977), and available phosphorus was measured using the Olsen extraction method (Olsen and Sommers 1982: Method 24-5.5.2).

To evaluate statistical differences between cultivated and uncultivated soils of different agricultural contexts, *t*-tests were used. Statistical analysis was performed using Corel Quattro Pro, Version 7.0, and it was conducted for all quantitative chemical and physical soil tests.

In addition to above analyses, granulometric testing was undertaken to measure the extent to which the natural surface was altered in building the gravel mulch features. Relative (or semi-quantitative) soil moisture was recorded using a moisture meter with a scale of 1 to 10. Six grids, scattered across six different gridded fields, were selected for these tests, and compared to adjacent non-gridded areas. Grids ranged from 5 to 9 m across. A 0.5 m by 0.5 m pit was excavated in each of these grids to depths of 5 cm and 10 cm. The excavated material was sieved using graduated screen sieves to separate rocks into size fractions of (1) 1/8 to 1/4 inch (0.32-0.64 cm); (2) 1/4 to 1/2 inch (0.32-1.27 cm); (3) 1/2 to 1 inch (1.27-2.54 cm); (4) and 1 to 6 inches (2.54-15.24 cm) to collect data on gravel weights by size fraction. Heavy cobbles larger than 6 inches were excluded from the sample because: (1) one or two spurious stones of this size would skew total weights; and (2) such a quantification exercise would only show what was is visually obvious (that is, non-gridded areas were strewn with larger cobbles while adjacent grid interiors contain very few and grid borders many of these larger stones). These data were compared to similarly excavated material from adjacent non-gridded areas to determine whether grid surfaces were mulched by adding gravel to the surface, or winnowed to remove gravel or cobbles.

BACKGROUND INFORMATION

Published soil mapping data and unpublished soil testing data for the SGF are reviewed in this section. Background information on the chemical and physical soil tests (pH, organic carbon, nitrogen, C:N ratio, total and available phosphorus, calcium carbonate equivalent, particle-size, and bulk density) used in this study is also presented, with a brief discussion of the agricultural significance of each measure of soil productivity. More detailed information on these soil tests is available elsewhere (Homburg 1994, Homburg and Sandor 1997, Sandor 1983).

Soil Mapping Data

The study area is included in the Continental-Latene-Pinaleno association on the general soil map of Arizona (scale=1:1,000,000); this soil association is characterized by "deep, gravelly, medium fine-textured, nearly level to steep soils on dissected alluvial fan surfaces" (Hendricks 1985: Plate 1). A more detailed soil map (scale=1:20,000) shows three soil map units for the SGF (Gelderman 1970: Map Sheet 7): (1) Bitter Springs-Pinaleno complex, 0-5% slopes, in the far western part of agricultural complex, where Locality 1 is located; (2) Pinaleno-Cave complex, 0-5% slopes, throughout most of the site; and (3) Pinaleno cobbly loam, 2-5% slopes, in the northeastern part of the site.

All three soil series are sparsely vegetated, calcareous, and they are in the Aridisol soil order. At the family level of the USDA Soil Taxonomy (Soil Survey Staff 1998), the Bitter Springs series is classified as loamy-skeletal, mixed, superactive, thermic Typic Calciorthids; the Cave series as loamy, mixed, superactive, thermic, shallow Typic Petrocalcids; and the Pinaleno series as loamy-skeletal, mixed, thermic Typic Haplargids. These soil series have little to no hazard of water and wind erosion, low to fair moisture holding capacity, medium to rapid runoff, and very slow to moderate permeability. Native vegetation is typically dominated by creosotebush, with some ocotillo, cholla, barrel cactus, annual grasses and forbs, and occasional shrubs of mesquite, wolfberry, and whitethorn and catclaw acacia. Rooting depth, which is estimated at about 60 to 90 cm for the Bitter Springs and Pinaleno series and 13 to 60 cm for the Cave series, is limited by a weakly to strongly cemented zone of calcium carbonate. From a modern mechanized agricultural perspective, these soils are not regarded as suitable for cultivation, due to their droughty nature, high gravel content, restricted rooting depth, low organic matter content, and low to medium natural fertility. It is noteworthy, however, that many archaeological projects have documented widespread evidence of ancient farming activity on soils similar to those of the SGF throughout much of Arizona. It is a testament to the skills and perseverance of the ancient farmers that they managed to farm successfully in so many harsh environments.

Previous Soil Testing Data from the Safford Gridded Fields

In 1984, Larry H. Humphrey and Gay Kincaide, archaeologists with the Safford District of the BLM, collected a few soil samples from the SGF for analysis. Three soil samples were collected from grid interiors at the SGF and submitted for routine soil analysis at the Soils, Water and Plant Tissue Testing Laboratory, Department of Soils, Water and Engineering, University of Arizona. Results of these soil tests are presented in Table 2.1, with nutrient concentrations determined in the solution phase. The Testing Laboratory concluded that soils from the SGF are suitable for cultivating corn, beans, and squash.

Table 2.1. Previous soil testing results obtained by the University of Arizona.

Sample ID	Lab No.	pH (1)	Electrical Conductivity (mmho/cm)	Soluble Salts (ppm)	Sodium (meq/L)	Potassium (meq/L) (2)	ESP (3)	Nitrate-N (ppm) (4)	Soluble Phosphorus (ppm) (5)
#1 - 982	1027	6.95	0.75	525	0.74	0.28	-0.66	4.83	1.23
#2 - 976	1028	7.85	0.45	315	0.91	0.22	-0.23	2.80	0.59
#3 - 981	1029	7.70	1.40	980	0.16	0.04	-1.18	39.14	0.59

1 - Paste with distilled water
2 - Water soluble potassium
3 - Estimated exchangeable sodium percentage. (Note: We assume that the negative ESP values Indicate that these samples were below levels of detection. Also, the units for the electrical conductivity values were not provided, but we assume they are in mmho/cm)
4 - From carbon dioxide extraction. Technicon reduction of nitrate reported as N.
5 - Carbon dioxide extraction and orthophosphate determination (Technicon).

Review of Soil Tests Used in This Study

Soil reaction, or pH, is defined as the degree of alkalinity or acidity of a soil. Soil reaction provides information on the availability of nutrients to plants. For noncalcareous soils, the optimal pH range for nutrient uptake is between 6.5 and 7.5 (Baize 1993). Nitrogen availability is greatest between pH 6 and 8 (Foth and Ellis 1988), and phosphorus availability is greatest between pH 6 and 6.5 (Tisdale, et al. 1985). A soil pH of 6.5 is considered optimal for cultivation of most varieties of maize. Organic carbon, a measure of organic matter, is one of the most useful characteristics for assessing soil fertility. Several beneficial properties are associated with soils having high organic matter contents, including increased water-and nutrient-holding capacities and improved tilth (Bear 1927; Brady 1999; Wild 1993). Soil organic matter is difficult to measure precisely, so it is commonly estimated by multiplying the organic carbon concentration by a conversion factor known as the Van Bemmelen factor, which is a variable that depends on the degree of humification; a conversion factor of 1.724 is typically used for plowed topsoils (Baize 1993, Nelson and Sommers 1982). Topsoils with less than 1 percent organic matter content have the lowest productivity, and soils exceeding 3 percent organic matter produce the most consistently high crop yields (Young 1982). Runoff agriculture provides a mechanism for adding organic matter to soils in the absence of artificial fertilizer additions (Sandor 1995). For example, the Tohono O'odham counter naturally low organic matter contents and losses due to crop uptake by placing fields on alluvial fans to intercept organic debris and minerals carried by runoff (Castetter and Bell 1942: 172). Nabhan found that nutrient-rich debris washed into Tohono O'odham floodwater fields averaged 4 percent organic matter, which is significantly higher than natural soil levels

(Nabhan 1983, 1984).

Nitrogen is usually the most limiting nutrient for agricultural production in Arizona soils (Doerge 1985). Nitrogen deficiencies are so severe in many desert soils that sustainable agriculture is impossible without fertilizer additions, naturally deposited organic debris, or nitrogen-fixing plants. Most nitrogen is associated with organic matter, which protects its release by microbial activity. The nitrogen cycle is extremely complex because many biological processes are involved and because nitrogen occurs in many forms during its cycle. Nitrogen absorbed by plants is usually in the form of nitrate-N (NO_3-N) and ammonium-N (NH_4-N), both of which are major constituents of inorganic nitrogen. Lower pH levels favor NO_3-N uptake and neutral pH's favor NH_4-N uptake (Tisdale, et al. 1985: 120).

Carbon: nitrogen (C:N) ratios provide an index of the stage and rate of organic matter decomposition by microorganisms. As microbes convert organic carbon to gaseous carbon dioxide, carbon is released to the atmosphere, nitrogen is combined into new protein molecules, and the C:N ratio narrows through time. High C:N ratios indicate that the soil contains high amounts of incompletely decomposed organic matter. Maize stalks have C:N ratios of about 40:1 (Hausenbuiller 1972: Table3.1), and agricultural soils usually have ratios between 8:1 and 15:1. Undisturbed topsoils that have reached equilibrium with environmental conditions often have ratios between 10:1 and 12:1 (Tisdale, et al. 1985), and ratios are usually lower in the soils of warm and dry climates than those of humid and cool regions (Brady and Weil 1999). Many modern cultivated soils have narrower ratios than comparable uncultivated soils (Jenny 1941, Sandor, et al. 1986).

Phosphorus is a plant macronutrient that is added to soil by natural chemical weathering and biological processes. Unlike soluble macronutrients, phosphorus usually occurs as a highly stable compound that is not easily mobilized, so it is an especially useful indicator of ancient cultivation effects. Because of its strong affinity with oxygen, virtually all soil phosphorus is in the form of phosphate. Small quantities of soluble phosphate are leached from the surface, but most phosphate is quickly fixed in compounds of low solubility (e.g., calcium phosphates above pH 7 or aluminum phosphates below pH 6). Consequently, most phosphorus is unavailable to crops, even in heavily fertilized soils where phosphorus accumulates to high levels.

Calcium carbonate in the soil originates from one or more sources, including the soil parent material, atmospheric inputs (that is, dust), and biogenic precipitates. Carbonate-enriched soils are represented by several stages of formation (Gile et al. 1966) and they are widespread in the Southwest (Gile et al. 1981, Machette 1965). Calcium carbonate equivalent (CCE) is a measure of the acid-neutralizing capacity of a liming material, and it is expressed as a weight percentage of pure calcium carbonate (Tisdale et al. 1985). Calcium carbonate is significant agriculturally because of the strong effect it exerts on soil chemistry, especially on pH and the availability of P and micronutrients such as Fe, Zn, Cu, and Mn (Fuller and Ray 1965, Yaalon 1957). The importance of calcium carbonate in buffering soil pH in the alkaline range is highlighted by the fact that about 10 tons of sulfuric acid per acre is required to neutralize every 1 percent calcium carbonate.

Bulk density is defined as the "mass of dry soil per unit bulk volume" (Soil Science Society of America 1987: 4). This soil property strongly influences aeration, permeability, moisture retention, seedling emergence, and root penetrability. Depending on soil texture, bulk densities in the range of 1.55 to 1.80 g/cm^3 may impede root growth (Wild 1993:117). Bulk densities are often highly variable, even for comparable soil horizons with similar textures, because of differences in size, shape, connectivity, and tortuosity of pores. Clay, clay loam, and silt loam topsoils commonly have bulk densities between 1.0 and 1.6 g/cm^3, and sands and sandy loams have values typically between 1.2 and 1.8 cm^3 (Brady and Weil 1999). Bulk density and aggregate size usually increase with depth, as the weight of overlying soil horizons increase, and organic matter content, root biomass, and faunal burrowing activity decrease. Cultivation can cause either increased or decreased bulk densities (Hausenbuiller 1972:81). Compaction is usually more severe in mechanized agricultural systems, but cultivation by no-tillage systems can still cause long-term compaction if organic matter is depleted, especially when native grasses and weeds fail to recover after fields are abandoned (Sandor et al. 1990).

Soil texture is defined at the relative proportion of particles smaller than 2 mm, including the clay (<2 μ), silt (2-50 μ), and sand (0.05-2 mm) fractions. Particle-size distribution is a significant soil property because virtually all physical and chemical processes depend on size of particulate matter (Murphy 1984). Twelve textural classes are defined in the USDA system (Soil Survey Staff 1993). Soil texture is one of the most useful properties for evaluating agricultural potential because it strongly affects soil permeability, cohesiveness, erodibility, cation exchange capacity, and the ability to maintain nutrients and water in the rooting zone (Glinski and Lipiec 1990, Homburg and Sandor 1997, Jeffrey 1987). Sandy soils tend to have low nutrient-and water-holding capacities, but are prone to wind erosion; silty soils have an intermediate nutrient-holding capacity, but are easily eroded and are subject to problems associated with surface sealing; clayey soils have a high nutrient- and water-holding capacity, but have a low permeability. Overall, loams, sandy loams, and silt loams are the most productive agricultural soils in terms of fertility and available water capacity.

RESULTS AND DISCUSSION

Soil Morphological Properties and Their Agricultural Implications

All six soil profiles are described in Appendix A. Included are morphological soil data for: (1) the PP 1 in a grid interior and T 2 next to PP 2 and a rock pile; (2) T 1 across two terraces and a rock alignment; and (3) a 40-cm deep shovel pit in a grid interior.

The profile descriptions, combined with observations of exposures on the eastern edge of Locality 1 above Peck Wash, indicate that a petrocalcic horizon (a Bkm, or carbonate-cemented layer that is completely indurated) characterizes most of Locality 1, including most of the areas where agricultural features were built. The top of the petrocalcic horizon is about 30 cm deep in PP 1 and other areas (Figure 2.3), but it was encountered at 40 to 45 cm depth in the agricultural terraces of Trench 1 (Figure 2.4). It is about 1 m thick at a minimum, and it is capped by thin laminae. These laminae form due to carbonate precipitation only after soil pores have been plugged, and such an advanced stage of carbonate accumulation (stage IV in the system of (Gile, et al. 1966) is significant for agricultural soils because water infiltration and root penetration is effectively blocked. The soil of the grid interior exposed in the profile of PP 1, where the petrocalcic horizon was documented in the greatest detail, was classified to the family level as Loamy, mixed,

Figure 2.3. Thick petrocalcic horizon exposed in Prospectors Pit 1.

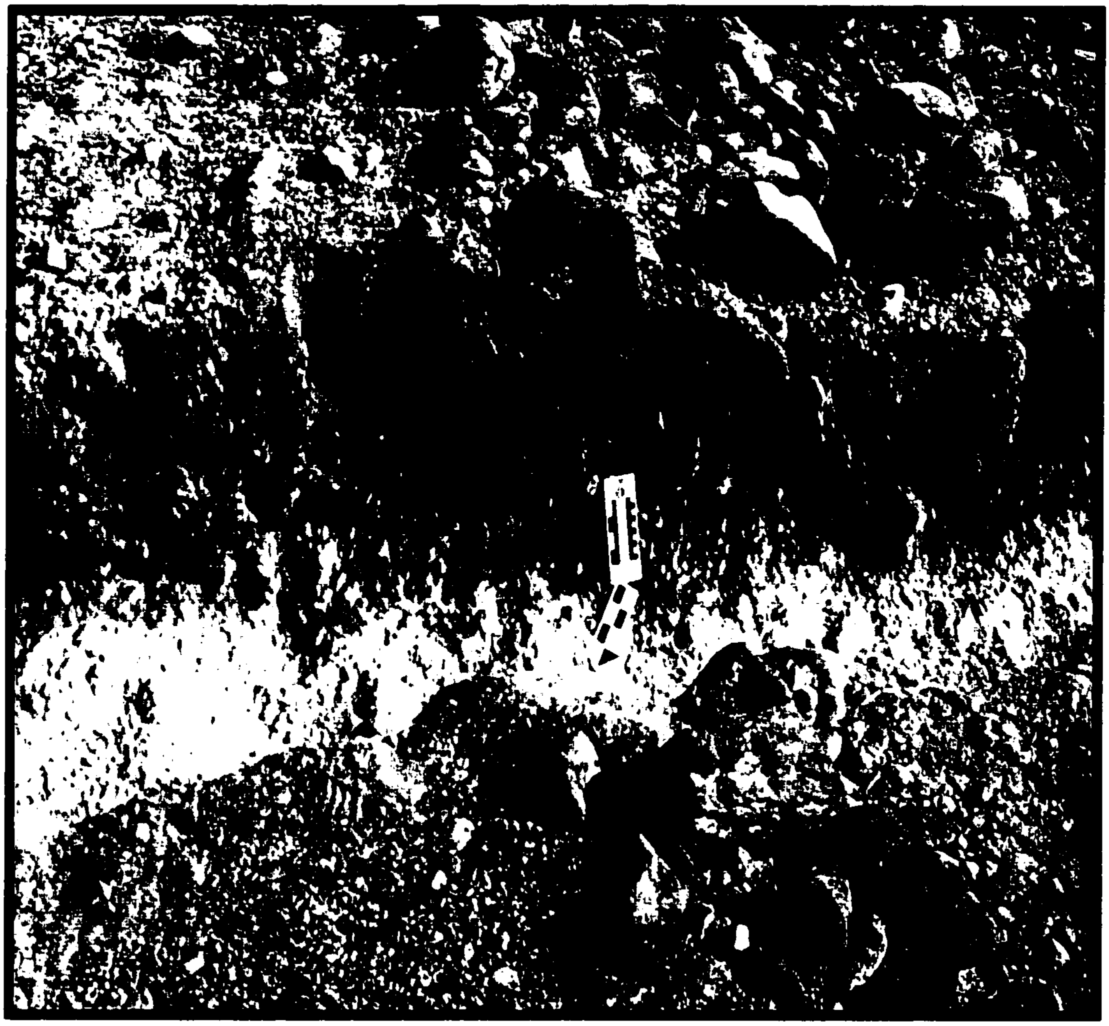

Figure 2.4. Shallow petrocalcic horizon below agricultural terraces and rock alignments.

superactive, thermic Typic Petrocalcid.

Areas with subsurface petrocalcic horizons are strongly associated with creosotebush, the plant that dominates the landscape. Creosotebush is better adapted and tends to dominate other plants in thin, drought-prone, alkaline soils, which accounts for its widespread distribution in the Western deserts of the U.S. (Solbrig 1977). Creosotebush can grow in soils as thin as 10 to 25 cm, where their rooting system is confined above a petrocalcic horizon (Barbour, et al. 1977), and they are an important source of biogenic carbonate for the soil, thus contributing to petrocalcic development (Gallegos and Monger 1997).

In parts of Locality 1, especially the lower landscape positions of the fan terrace, an argillic horizon (a Bt horizon with significant alluvial clay accumulation) was encountered at very shallow depths of 3 to 4 cm. Well-developed argillic horizons occur in areas with less gravel in the soil than where the petrocalcic horizons formed. Argillic horizons were found to be at least 1 m thick in PP 2 (Figure 2.5), where it is coterminous with a calcareous zone (a Btk horizon) marked by carbonate filaments, masses, and gravel coatings. Interestingly, a buried argillic horizon marking a lithological discontinuity was identified in PP 2. It is unknown if buried petrocalcic horizons underlie any of the argillic horizons, because we only dug to a depth of 1 m in PP 2. The soil of PP 2 was classified to the family level as a Fine-loamy, mixed, thermic Calcic Paleargid. In the shovel pit placed in a grid interior, the argillic horizon was only 7 cm thick, overlying a Bk horizon. Some evidence of clay illuviation (though not enough to qualify as an argillic horizon) was noted in the Btkm horizon found only in Trench 1, in the upper agricultural terrace position immediately below the rock alignment. It is noteworthy that creosotebush was concentrated in this position, evidently due

Figure 2.5. Argillic horizon in Prospectors Pit 2, surrounded by desert pavement.

to lateral water seepage from the gravel-mulched soil of the terrace alignment.

Argillic horizons are significant agriculturally because they effectively impede infiltration and maintain moisture in the rooting zone, and enhance available water capacity. Observations throughout the Southwest indicate a widespread pattern of dryland fields associated with subsurface argillic (Homburg 1994, Homburg 1997, Homburg and Sandor 1997, Sandor 1995, Sandor and Homburg 1997).

Topsoils (or A horizons) are generally thin throughout Locality 1, at less than 5 cm, but they are approximately tripled in thickness to about 15 cm in the lower agricultural terrace fill deposits of Trench 1. This is an important soil difference between agricultural terrace soils and other agricultural soils, due to the thickening of the rooting depth. This soil difference suggests that terraces may have served an agricultural function distinct from other features, perhaps with different crops.

Gravelly and cobbly to extremely gravelly and cobbly soils are characteristic of most of Locality 1 and the SGF in general, both surficially and in the subsurface. A desert pavement covers most of the surface of Locality 1, and most exposed rocks have coatings of desert varnish. Desert varnish forms mainly due to microbial activity at pHs below 9.0, and the varnish consists of microscopic layers of clay minerals, oxides and hydroxides of iron and manganese, admixed with detrital silica, calcium carbonate, and organic matter (Dorn and Oberlander 1981). These coatings are thought to take hundreds to thousands of years to form (Dorn and DeNiro 1984, Elvidge 1982). Thicker coatings mark the most stable landscape positions, because such traces would have been removed if the surface had been highly eroded, disturbed by human activity, or if deposition was still active. Desert pavement and varnish are most strongly expressed in the vicinity of PP 2. Many of the cobbles that were used to build agricultural features have coatings of varnish, but with irregular orientations. The variable orientations indicate that humans had indeed moved cobbles to construct agricultural rock features. Cation ratio ($K^+ + Ca^{2+}/Ti^{4+}$) and radiocarbon dating has been used to determine when desert varnish formed, and thus when the rocks were first exposed (Dorn, et al. 1986). In fact, at the start of this project it was thought that these methods might help date construction of the agricultural rock through analysis of varnish formed on the parts of rock surfaces exposed after construction. The reliability of these methods for dating purposes, however, was subsequently refuted, due to the discovery that varnish formation does not occur within a closed system. Exogenous windblown carbon from outside of the system (e.g., nearby Pleistocene playas) may be deposited on the rock surface and then incorporated within the varnish. Such a process can produce erroneous radiocarbon dates (that is, ones unrelated to the age of surface exposure).

The gravelly and cobbly desert pavement armors the soil, negates raindrop impacts on the soil, and thereby counters erosional processes. These rocks also serve a number of functions pertinent to agricultural production. For example, they provided the raw material for building the agricultural features, and it is doubtful the features would have been built if they had to be hauled in from elsewhere. Lithologically, the rocks of the agricultural features are identical to those of the local alluvium, which clearly indicates they were obtained on-site. Importantly, the rocks also function to increase the depth of wetting after rainfall events by concentrating infiltration to soil between the rocks, thus reducing evaporative loss and improving agricultural productivity (Alderfer and Merkle 1943, Choriki et al. 1964, Fairbourn 1973, Homburg and Sandor 1997, Lightfoot 1990, Mehuys et al. 1975, Saini and MacLean 1967). In addition, because the rocks retain heat, they warm the soil at night, thereby reducing the potential for frost damage to crops. Although the rocks provide several advantages for agricultural production, they also limit agricultural production in certain ways. An increased volume of rocks in the soil proportionally reduces the capacity for water and nutrient storage, as well as the volume available for root exploration. Despite these potential negative effects, overall, the rocks served essential functions that the ancient farmers took advantage of in this semiarid climate.

Physical and Chemical Soil Testing Data

Soil chemistry, bulk density, and particle-size data for the soil profiles are summarized in Tables 2.2 and 2.3 for the soil profiles and in Tables 2.4 and 2.5 for the agricultural soils and their controls. Mean soil test values for the agricultural soils are presented graphically as histograms in Figure 2.6. Tables 2.6 and 2.7 show all of the mean values and standard deviations, and Table 2.8 summarizes the *t*-test probability values for pair-wise comparisons of comparable agricultural and uncultivated contexts.

Most uncultivated soils in Locality 1 are moderately alkaline, with pHs in the range of 8.0 to 8.5, reflecting the calcareous nature of the soils. At these levels, the availability of some nutrients is limited, especially phosphorus and most micronutrients (iron, manganese, zinc, copper, cobalt, and boron), but nitrogen, potassium, calcium, magnesium, sulfur, and molybdenum are readily available (Homburg 1994: Fig. 11.9). Although micronutrient availability is reduced at these pH levels, it is worth noting that micronutrient deficiencies are

Table 2.2. Soil chemistry and bulk density data for soil profiles.

Soil Horizon	Depth (cm)	pH	Organic C (g/kg)	CCE (%)	N (g/kg)	Total P (mg/kg)	Avail. P (mg/kg)	Bulk Density (g/cm3)
PP1								
A	0-2	8.1	9.8	7.2	0.96	756	14.2	--
Abk	2-12	8.7	6.2	9.8	0.76	649	11.9	1.30
Bk	12-30	8.4	9.0	14.4	1.01	635	11.5	--
PP2								
A	0-4	9.1	0.7	9.5	0.22	628	4.8	--
Btk1	4-17	8.5	3.3	14.6	0.41	705	8.8	1.35
Btk2	17-40	8.5	0.7	24.0	0.36	911	6.5	1.51
Btk3	40-59	8.5	1.6	33.4	0.37	1428	6.8	1.39
2Btk1	59-77	8.4	0.7	42.9	0.27	1390	8.7	1.35
2Btk2	77-100	8.6	0.7	37.1	0.20	1043	7.0	1.69

Note: CCE = calcium carbonate equivalent; bulk density values are missing for samples with weakly aggregated peds.

Table 2.3. Particle-size data (%) for soil profiles.

Soil Horizon	Depth (cm)	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Total Sand	Coarse Silt	Fine Silt	Clay
PP1										
A	0-2	5	6	8	10	28	56	24	9	11
Abk	2-12	5	5	8	11	28	57	23	11	10
Bk	12-30	7	5	7	2	33	54	21	15	9
PP2										
A	0-4	5	4	7	5	31	53	23	17	7
Btk1	4-17	3	4	4	2	15	28	17	26	29
Btk2	17-40	5	4	4	2	15	30	11	26	33
Btk3	40-59	3	5	6	2	19	35	14	31	20
2Btk1	59-77	0	3	4	2	13	22	13	27	38
2Btk2	77-100	0	2	2	0	18	22	21	15	42

Table 2.4. Soil chemistry and bulk density data for grid features, terraces, rock piles, and controls.

Sample Type and Location	pH	Org. C (g/kg)	CCE (%)	N (g/kg)	C:N Ratio	Total P (mg/kg)	Avail. P (mg/kg)	Bulk Density (g/cm3)
Grid Alignment								
SP 1	7.7	5.9	8.0	0.62	9.6	626	20.2	1.42
SP 3	7.7	6.0	4.7	0.52	11.5	666	26.1	1.39
SP 5	7.4	3.9	5.8	0.41	9.6	559	11.5	1.36
SP 7	7.7	5.6	3.8	0.54	10.2	496	10.4	1.43
SP 9	7.5	5.3	5.7	0.51	10.6	662	11.4	--
SP 11	7.9	3.9	6.2	0.35	11.3	529	8.6	1.28
SP 13	7.9	5.3	6.9	0.41	13.0	691	10.6	1.43
SP 15	8.1	5.5	9.2	0.59	9.4	597	6.2	--
Grid Interior								
SP 2	8.0	4.6	1.9	0.42	10.9	723	9.4	1.45
SP 4	8.1	5.0	4.0	0.42	11.9	965	9.8	1.47
SP 6	7.5	3.3	2.1	0.32	10.4	484	13.8	--
SP 8	7.8	4.8	3.5	0.41	11.8	691	9.1	1.36
SP 10	7.5	2.3	5.9	0.27	8.3	640	5.9	--
SP 12	7.7	1.6	9.1	0.24	6.9	699	10.5	1.42
SP 14	8.2	3.9	11.6	0.40	9.7	865	5.2	--
SP 16	8.2	3.3	12.0	0.35	9.3	833	5.2	1.38
Grid Control, SE Locality 1								
SP 27	8.3	1.4	9.2	0.34	4.1	587	4.9	1.50
SP 28	8.4	2.5	11.0	0.41	6.0	715	5.2	1.48
SP 29	8.5	7.5	15.1	0.57	13.0	750	5.3	1.49
Grid Control, West of PP 2								
SP 30	8.5	3.3	9.3	0.40	8.3	746	9.7	1.17
SP 31	8.4	4.0	10.7	0.42	9.6	787	7.2	1.12
SP 32	8.4	4.7	12.5	0.41	11.4	613	5.2	1.30
Below Terrace Alignment								
SP 17	8.1	3.0	11.7	0.58	5.2	657	10.2	--
Trench 1a	8.1	3.4	6.2	0.41	8.2	596	5.9	--
SP 20	7.6	3.0	6.2	0.71	4.2	699	13.3	1.47
Terrace Rock Alignment								
SP 18	7.8	5.1	5.5	0.45	11.3	510	11.3	--
Trench 1b	7.6	5.5	6.0	0.60	9.2	591	15.4	1.45
SP 21	7.8	4.6	5.1	1.08	4.3	710	26.5	1.29
Above Terrace Alignment								
SP 19	8.0	5.5	4.4	0.42	12.9	584	5.3	1.40
Trench 1c	7.7	8.6	4.1	0.45	19.1	647	9.2	1.49
SP 22	8.2	7.3	3.7	0.53	13.8	477	7.0	1.14
Terrace Control								
SP 33	8.2	11.7	5.8	0.59	19.9	432	11.6	1.32
SP 34	8.2	9.5	6.2	0.64	14.7	457	10.5	1.38
SP 35	8.0	5.0	5.2	0.69	7.2	493	12.4	1.43
Rock Pile								
Trench 2	9.0	2.5	6.0	0.40	6.3	372	5.4	1.45
SP 23	7.7	4.1	9.1	0.42	9.6	560	8.9	1.28
SP 25	8.1	3.0	7.7	0.46	6.5	432	17.5	--
Rock Pile Control								
Trench 2	9.3	9.3	12.4	0.42	22.4	672	5.9	1.41
SP 24	8.3	8.9	10.2	0.42	21.3	632	3.7	--
SP 26	8.2	4.5	5.6	0.42	10.7	651	7.1	--

Note: CCE = calcium carbonate equivalent; bulk density values are missing for samples with weakly aggregated peds.

Table 2.5. Particle-size data (%) for grid features, terraces, rock piles, and controls.

Sample Type and Location	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Total Sand	Coarse Silt	Fine Silt	Clay
Grid Alignment									
SP 1	4	4	6	16	14	44	19	14	23
SP 3	4	5	8	18	18	53	20	10	17
SP 5	3	4	4	11	18	41	25	15	19
SP 7	5	3	3	2	25	38	27	16	19
SP 9	7	6	7	11	18	49	26	11	13
SP 11	4	5	5	14	19	47	26	13	14
SP 13	5	5	6	11	19	47	22	15	16
SP 15	7	6	5	10	12	41	20	17	22
Grid Interior									
SP 2	2	3	5	14	17	41	23	13	23
SP 4	3	3	5	12	20	43	23	15	19
SP 6	5	4	5	12	18	43	25	13	19
SP 8	3	4	6	14	18	45	22	18	16
SP 10	7	6	9	17	18	58	22	11	10
SP 12	6	5	6	15	21	53	25	10	11
SP 14	9	6	7	14	18	54	21	13	11
SP 16	3	3	6	10	20	42	24	19	14
Grid Control, SE Locality 1									
SP 27	3	5	7	11	25	48	21	15	16
SP 28	3	4	7	13	19	46	17	19	18
SP 29	4	3	6	18	14	44	17	21	18
Grid Control, W of PP 2									
SP 30	5	5	6	15	21	51	32	6	11
SP 31	5	5	6	16	21	54	24	14	8
SP 32	5	5	5	14	22	51	25	14	10
Below Terrace Alignment									
SP 17	9	7	7	4	25	51	26	13	10
Trench 1a	12	7	6	8	20	53	28	10	8
SP 20	5	6	7	9	24	51	29	12	8
Terrace Rock Alignment									
SP 18	8	8	8	11	17	53	24	12	11
Trench 1b	5	5	5	7	20	42	33	14	11
SP 21	5	6	6	0	28	45	32	14	9
Above Terrace Alignment									
SP 19	5	6	6	4	27	48	29	14	9
Trench 1c	4	4	4	0	28	40	36	15	9
SP 22	5	5	6	0	29	45	32	13	10
Terrace Control									
SP 33	5	5	5	2	25	43	27	12	17
SP 34	5	6	6	2	26	46	26	11	18
SP 35	5	5	6	12	16	44	29	12	15
Rock Pile									
Trench 2	4	4	6	16	12	42	18	21	19
SP 23	3	6	11	27	11	58	16	14	12
SP 25	5	6	8	8	33	59	21	10	9
Rock Pile Control									
Trench 2	2	4	4	0	18	28	14	31	27
SP 24	4	4	6	0	36	49	16	19	16
SP 26	3	5	6	17	21	53	25	12	9

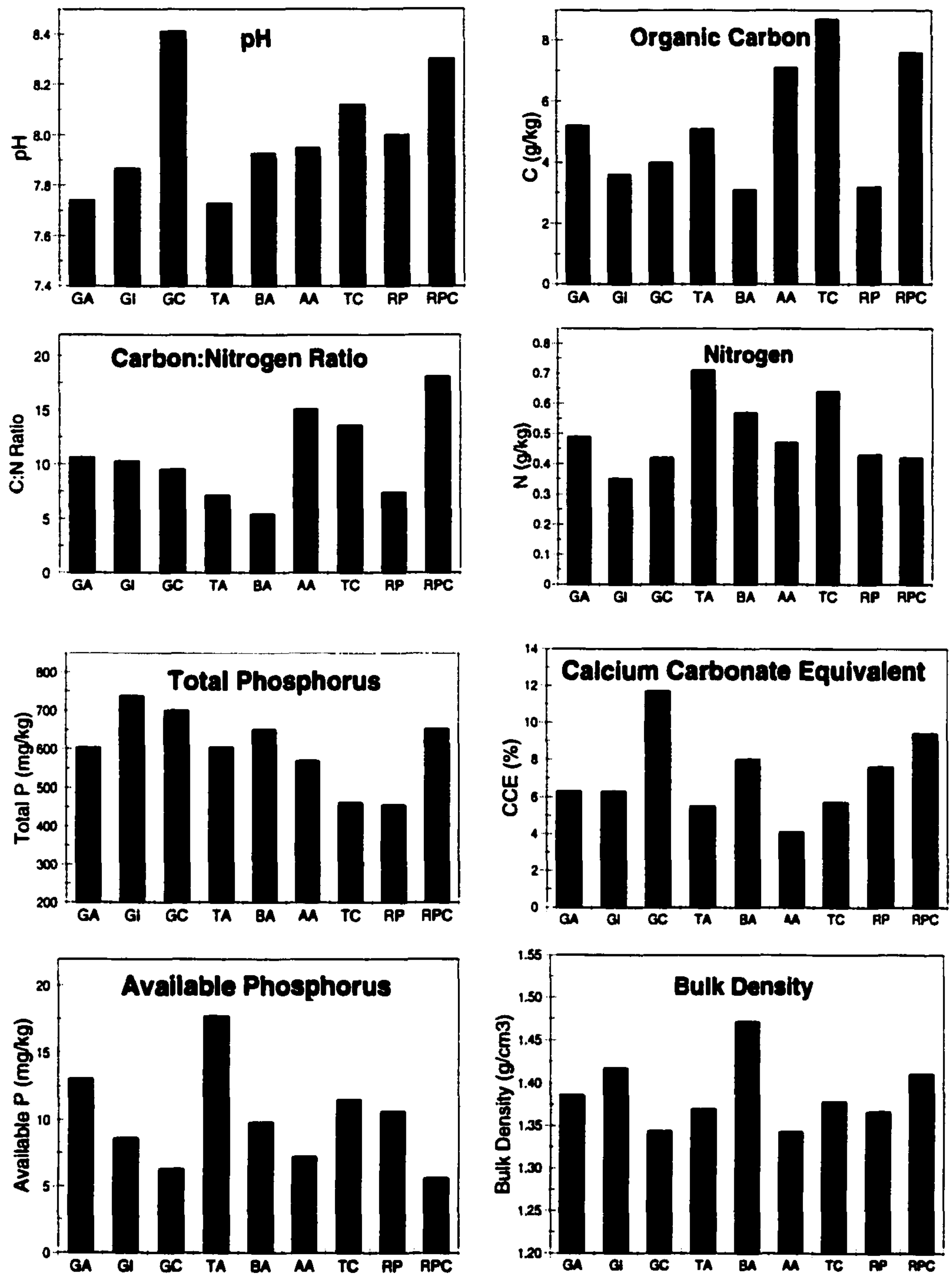

Figure 2.6. Histograms of soil data (means) by sample context. Sample contexts: GA - grid alignment (n=8); GI - grid interior (n=8); GC - grid control (n=6); TA - terrace alignment (n=3); BA – below terrace alignment (n=3); AA - above terrace alignment (n=3); TC - terrace control (n=3); RP - rock pile (n=3); RPC – rock pile control (n=3).

Table 2.6. Means (X) and standard deviations (σ') for soil chemistry and bulk density tests.

Sample Context	pH		Organic C (g/kg)		CCE (%)		N (g/kg)		C:N Ratio		Total P (mg/kg)		Available P (mg/kg)		Bulk Density (g/cm3)	
	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'
Grid Alignment	7.7	0.0	5.2	0.8	6.3	1.7	0.49	0.10	15.8	1.2	603	70	13.1	6.6	1.39	0.06
Grid Interior	7.9	0.3	3.6	1.2	6.3	4.1	0.35	0.07	22.5	1.7	738	149	8.6	3.0	1.42	0.04
Grid Control	8.4	0.1	4.0	2.1	11.7	2.2	0.42	0.08	20.0	3.3	700	81	6.3	1.9	1.34	0.17
Below Alignment	7.9	0.3	3.1	0.2	8.0	3.2	0.57	0.15	13.9	2.1	650	52	9.8	3.7	1.47	0.00
Terrace Align.	7.7	0.1	5.1	0.5	5.5	0.5	0.71	0.33	10.9	2.6	604	100	17.7	7.9	1.37	0.12
Above Alignment	8.0	0.3	7.1	1.6	4.1	0.4	0.47	0.05	16.9	3.4	569	86	7.2	2.0	1.34	0.18
Terrace Control	8.1	0.1	8.7	3.4	5.7	0.5	0.64	0.05	12.7	6.4	461	30	11.5	0.9	1.38	0.05
Rock Pile	8.0	0.7	3.2	0.8	7.6	1.6	0.43	0.03	18.6	1.9	455	96	10.6	6.2	1.37	0.12
Rock Pile Control	8.3	0.6	7.6	2.7	9.4	3.5	0.42	0.00	19.8	6.5	652	20	5.6	1.7	1.41	0.00

Table 2.7. Means (X) and standard deviations (σ') for particle-size analysis.

Sample Context	VCS		CS		MS		FS		VFS		Total Sand		Coarse Silt		Fine Silt		Clay	
	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'	X	σ'
Grid Alignment	5	1.5	5	1.1	6	1.6	12	4.7	18	3.8	45	5.1	23	3.4	14	2.5	18	3.6
Grid Interior	5	2.5	4	1.4	6	1.4	14	2.1	19	1.4	47	6.5	23	1.7	14	3.3	15	4.7
Grid Control	4	1.1	4	0.9	6	0.6	15	2.5	20	3.7	49	3.7	23	5.8	15	5.4	13	4.2
Below Alignment	6	3.8	6	0.4	6	0.4	6	2.7	22	2.7	46	1.2	30	1.5	13	1.5	10	0.8
Terr. Alignment	8	1.6	6	1.7	7	1.4	7	5.5	23	5.7	52	5.5	28	4.9	12	1.3	9	1.0
Above Alignment	5	0.9	5	0.8	5	1.1	1	2.0	28	0.7	44	4.0	32	3.3	14	1.0	9	0.6
Terrace Control	5	0.2	5	0.6	6	0.6	5	5.9	22	5.4	44	1.3	27	1.6	12	0.8	17	1.7
Rock Pile	4	0.6	5	0.9	8	2.6	17	9.5	19	12.4	53	9.4	19	2.8	15	5.2	13	4.9
Rock Pile Cont.	3	1.0	4	1.0	6	1.1	6	9.9	25	9.4	43	13.6	18	5.8	21	6.5	17	8.9

Table 2.8. *t*-Test probabilities of pair-wise comparisons of cultivated and uncultivated soils.

Sample Comparison	pH	Org. C	CCE	N	Tot. P	Av. P	Bulk Density	Sand	Silt	Clay
Gridded Features										
GA vs. GI	0.36	0.01**	0.99	0.00**	0.04*	0.10	0.34	0.41	0.99	0.25
GA vs. GC	0.00**	0.09	0.00**	0.10	0.03*	0.03 *	0.58	0.13	0.78	0.05*
GI vs. GC	0.00**	0.50	0.02*	0.11	0.59	0.12	0.39	0.61	0.74	0.41
Rock Piles										
RP vs. RC	0.55	0.05	0.46	0.64	0.03*	0.25	0.45	0.37	0.23	0.53
Terrace Features										
BA vs. TA	0.36	0.00**	0.25	0.53	0.51	0.19	-	0.18	0.38	0.08
BA vs. AA	0.93	0.01*	0.10	0.34	0.23	0.35	-	0.04*	0.05 *	0.34
BA vs. TC	0.37	0.05*	0.28	0.47	0.00**	0.47	-	0.00**	0.82	0.00**
TA vs. AA	0.28	0.10	0.01*	0.27	0.23	0.09	0.87	0.62	0.50	0.20
TA vs. TC	0.01*	0.14	0.64	0.74	0.08	0.25	0.87	0.54	0.36	0.70
AA vs. TC	0.39	0.50	0.00**	0.02*	0.11	0.03*	0.77	0.99	0.06	0.00**

* - significant at $\alpha = 0.05$; ** - significant at $\alpha = 0.01$

Note: no t-tests were performed for some bulk density comparisons due to missing data.

GA = grid rock alignment; GI = grid interior; GC = grid control;
RP = rock pile; RC = rock pile control
BA = below terrace alignment; TA = terr. rock alignment; AA = above terr. alignment; TC = terr. control

rare in soils throughout the Southwest (Doerge 1985). In T 2 in the northern part of Locality 1, next to PP 2, we found the surficial uncultivated soils to be very strongly alkaline, with pHs of 9.1 to 9.3. Soils with a pH above 8.5 nearly always have exchangeable sodium percentages of 15 or more (Fireman and Wadleigh 1951), and at these levels, serious problems can be caused by reductions in water uptake by plants and dispersal of soil aggregates. Although reduced agricultural productivity would result from pH levels above 8.5, such soils appear to be very limited extent in Locality 1, so they probably did not pose serious problems to the ancient farmers. However, we did find some highly calcareous and possibly very alkaline soils in some clast-free grids in the large gridded field area just east of

Peck Wash and Locality 1.

An important finding is that pH levels are consistently reduced in all cultivated soils compared to their controls, to levels that improve overall nutrient availability. We found the largest pH reductions in the grid alignment and interior soils, with decreases averaging 0.7 and 0.5 units for these features, respectively (see Table 2.6), and these differences are statistically significant (see Table 2.8). The lower pH of these soils is consistent with their lower calcium carbonate equivalent. For the terrace features, the greatest pH reductions were found within and immediately below the alignments, which suggests these are favorable planting locations. The rock pile soils have reduced pHs, but not at significant levels. The lack of statistical significance in this apparent trend may be a function of small sample size.

Mean organic carbon levels in uncultivated soils vary between the sets of control samples, with the terrace and rock pile controls averaging 8.7 and 7.6 g/kg (or about 1.5% and 1.3% organic matter, respectively, based on the Van Bemmelen factor), which is nearly double that of grid controls. There is no statistical difference between either the grid interiors or alignments and their controls, but organic carbon content is significantly higher in the alignments than the interiors. This finding suggests that organic carbon is conserved by the grid alignments, and that the alignments are favorable planting locations. In comparing the terrace features, the terrace alignments and terrace positions immediately below the alignments, where creosotebush is concentrated, have significantly less organic carbon than their controls, possibly due to cultivation effects. Moreover, the rock pile soils have reduced organic carbon levels, but the difference is not statistically significant.

Overall, organic matter levels estimated by the Van Bemmelen factor are low at the

SGF, usually less than 1 percent in the cultivated soils. The naturally low organic matter content is due to aridity, low biomass production, and high temperatures that promote rapid oxidation and decomposition of organic debris. It is noteworthy that the Hopi successfully farm soils with organic matter contents similar to those of the SGF, through their management practices and possibly through the use of varieties of maize with relatively low nutrient requirements (Sandor 1983: 253-254). In semiarid regions of Arizona, natural organic matter levels are usually between 1 and 1.5 percent, which is consistent with the uncultivated terrace and rock pile controls of the SGF. Organic matter levels in cultivated soils at the SGF vary widely, from about 0.3 to 2.1 percent, with most falling between about 0.5 and 0.9 percent; these levels, though not ideal, are sufficient for growing many crops.

No statistical differences were noted in nitrogen levels between agricultural soils and their controls, with one exception; the terrace position above alignments had significantly reduced nitrogen levels compared to the controls. The only other statistical difference is the elevated nitrogen levels in the grid alignments compared to the controls. Soils associated with agricultural rock features have similar or slightly elevated nitrogen levels compared to uncultivated soils, which suggests that rocks act to conserve nitrogen stores. Alternatively, the elevated nitrogen levels may be result of post-cultivation vegetation associations with the rock features. Nitrogen and organic carbon trends parallel one another for the grid alignments, interiors, and controls. These trends were not found for the other agricultural contexts, possibly because of differences in organic matter decomposition or production, or simply a function of small sample size.

There is little difference in the mean carbon: nitrogen ratios between the gridded alignments and interiors and their controls, but the controls have higher ratios than the soils of rock pile and those within and below the terrace alignments. C:N ratios of cultivated soils are mainly in the range of 6:1 to 11:1, which indicates that most organic debris is highly decomposed, a form in which much of the organic matter is available to plants. C:N ratios between 8:1 and 10:1 are typical for desert soils in the Southwest, due to rapid organic matter decomposition rates (Fuller 1975: 25).

Many agricultural contexts, including grid alignments and the terrace positions above alignments, have significantly lower total phosphorus levels than their controls. In addition, the grid alignments have significantly reduced total phosphorus levels compared to the interiors. Because total phosphorus levels are slow to change in the soil, reductions in these agricultural contexts likely could reflect cultivation effects. More important to agricultural production, however, is the amount of plant-available phosphorus, and soils of all agricultural rock features have elevated levels compared to their controls. These differences are statistically significant for the grid and terrace alignments. Phosphorus requirements for crops are not well understood for many Arizona soils, but available phosphorus levels less than 2 mg/kg (or 2 ppm) are usually considered low, and values above 5 mg/kg are considered sufficient (Doerge 1985). Consequently, all of the cultivated SGF soils are sufficient in available phosphorus.

No statistical differences were noted in bulk density values, so there is no indication that cultivation caused significant long-term compaction. Even so, it is possible that soils were compacted during cultivation but have since recovered. There is now considerable overlap in the bulk density values of cultivated and uncultivated soils. The bulk densities are mainly between about 1.3 and 1.45 g/cm^3, and none of the samples exceed levels of 1.55 g/cm^3, the level at which root growth can be restricted. The extensive petrocalcic horizons of the SGF, however, strongly limit root growth.

Surface soil textures consist mainly of loams and sandy loams, which are good textural classes for holding high amounts of plant-available moisture. The high sand content (generally between 40 and 60 percent of the <2 mm fraction) promotes good aeration and rapid water infiltration into the rooting zone. The clay fraction has an especially profound effect on soil moisture retention and uptake of water and nutrients by plant roots; clay levels near the surface of the SGF are mainly between 10 and 23 percent, which is a range that is productive agriculturally. Vertical textural variability on the alluvial fan terrace of the SGF, caused by both soil horizonation (that is, soil formation) and sedimentary stratification, promotes both moisture retention and lateral water flow in the rooting zone. Subsurface gravel/cobble content is high, usually between 20 and 70 percent. As noted in the previous section on soil morphology, coarse rock fragments lower the water- and nutrient-holding capacity of the soil, but they effectively increase the depth of wetting in the soil after a runoff event and serve an important mulching function.

Overall, few statistical differences were noted between the sand, silt, and clay contents of cultivated and uncultivated soils. Clay content was found to be significantly higher in the grid alignments than the controls, and terrace positions above and below the alignments have significantly less clay than the controls. Significantly more sand and less silt were found below terrace alignments compared to above the alignments. Sand content is consistently higher in the rock pile soils than the controls, possibly due to the rocks trapping windblown sand; this difference, however, is not statistically significant, probably due to the small sample size. If aeolian sand has indeed been entrapped, this process may or may not be a post-cultivation effect on the rock piles.

Granulometric Tests

If grid surfaces were mulched with lithic materials, there would be noticeably more gravel within the grids, especially more of the size fractions dumped onto the grid surfaces during the mulching process. We found that grid interiors contain an average 24 percent less gravel (by weight) than adjacent areas outside of the grids, and an average 70 percent less of the larger cobbles (1 to 6 inches) within the upper 5 cm of the 0.5 m by 0.5 m test pits (Table 2.9). Few larger cobbles (>6 inches) were pulled from test pits in grid interiors, yet many such cobbles were found used as border stones. Furthermore, for every size fraction there is a greater quantity in the upper 5 cm than in the 5 to 10 cm level, except for the 1 to 6 inch fraction, where there is 64% less of this size material (yet 5% more of this fraction in the upper 5 cm outside of the grids; Table 2.10). This finding demonstrates intentional cultural modification of the surface layer of soil in grid interiors, where there is less gravel as a whole than outside for grids, and particularly fewer cobbles larger than 1 inch due to removal during construction of grid borders. Rather than being mulched, the surfaces of grid interiors were apparently winnowed in an effort to thin out coarser gravel and move the cobbles to grid borders. This agrees with the construction hypothesis first offered by Hough (1907) and Russell (1908), and subsequently assumed by others that inspected these grids. The grid

Table 2.9. Percent change (+ or -) in weight of lithic material within grids compared to that outside of grids.

Size Fraction (inches)	Depth 0-5 cm	5-10 cm	Mean
1.0-6.0	-70	-12	-42
0.5-1.0	-22	-22	-22
0.25-0.5	-0.8	-26	-13
0.125-0.25	+8	-17	-4
Total	-29	-18	-24

Table 2.10. Percent change (+ or -) in weight of lithic material in 0-5 cm level compared to 5-10 cm level within and outside of grids.

Size Fraction (inches)	Within Grid	Outside Grid
1.0-6.0	-64	+5
0.5-1.0	+27	+27
0.25-0.5	+29	+4
0.125-0.25	+25	+3
Total	-3	+10

interiors of the SGF were not mulched, meaning that a more or less uniform layer of gravel or cobbles was not prepared across the planting surface, unless the principal planting surface was to be the grid borders. In the process of clearing the gravel and cobbles from fields, the linearly piled clasts were placed to form grid borders, and they contributed to the retention of moisture across the entire surface of gridded fields.

Soil Moisture: The Cobble-Mulch Effect

Control of evaporation is one of the most important goals of soil management aimed at improving the supply of water to crops (Heinonen 1985). The amount of moisture in the soil at the time of spring planting significantly affects the survival and success of crops, especially in semiarid and arid soils. In areas like the exposed and windy terraces on which the SGF were built, the gravelly surfaces and heavy cobble borders promote retention of even greater amounts of soil moisture compared to bare soils (Benoit and Kirkham 1963, Homburg and Sandor 1997, Lightfoot and Eddy 1994). The size of the grids may have even been limited by reduced soil moisture away from cobble borders in large fields; if grids are made too big, their centers will be noticeably drier because of greater evaporative effects away from the borders.

Relative soil moisture tests supplied data for comparing six individual grids from different gridded fields (the same ones sampled for granulometric analysis) with adjacent non-gridded areas to determine if grids aided crop growth by retaining moisture. Precipitation data provided by Russell S. Vose of the Office of Climatology, Arizona State University, indicates that precipitation in the months preceding our fieldwork in mid-March were typical for the study area. A total of 55 mm (2.17 inches) of rain was recorded in the two and half months before moisture data were collected, including 34 mm in January, 14 mm in February, and 7 mm in March. About 18 mm of rain fell about two weeks before fieldwork, so soil moisture in the upper 5 cm had some time to dry through losses to drainage, evaporation, and plant uptake.

Soil moisture data were collected from the center and rock border area of each sample grid. An average two-fold increase in moisture was recorded inside the grids compared to adjacent areas outside the grids (2.6-fold increase in the upper 5 cm and 1.8-fold increase in the 0-10 cm level (Table 2.11). Several additional grids were randomly sampled in the upper

Table 2.11. Relative measures of moisture content within and outside of grids (expressed as mean readings on a scale of 1 to10).

Depth (cm)	Within Grid	Outside Grid	Magnitude of Increase Within Versus Outside Grid
0-5	2.8	1.1	2.6 X
5-10	3.8	2.2	1.8 X
All (0-10)	3.3	1.6	2.0 X

5 cm at the center, just inside the upslope and downslope borders, and at random points inside each grid. These measures of soil moisture were then compared to readings collected from surfaces outside of the gridded fields. There was no significant difference in moisture levels from point-to-point within grids but, just as in the more controlled tests, moisture readings inside of grids were double those of outside of grids. These data validate earlier, but untested, assumptions that the SGF served as water retention/water control features (Gilman and Sherman 1975, Stewart 1939, Stewart 1940).

Several agricultural terraces and associated rock alignments were also sampled at random in the upper 5 cm. Moisture readings immediately upslope of the cobble dams were similar to those taken inside of grids, and readings on adjacent unterraced slopes registered about half that of terraces upslope of rock alignments. These data show that agricultural terraces built on steeper slopes offered similar moisture retention benefits to that of grid features built on more gently sloping terrain. Rock mulch associated with both the terraced and gridded field areas would function to lower crop stress and increase agricultural yields.

Some Speculation about Likely Cultivars

An especially puzzling and elusive aspect of this project is determining what crops were, or might have been, cultivated. Soil data alone cannot answer this question. The most direct evidence may be supplied by microfossil (pollen and phytolith) data. Nevertheless, soil properties do provide some important clues about potential crops, especially when evaluated in the context of soil and native plant associations relative to prehistoric agricultural features.

We find it difficult to imagine that the ancient farmers of SGF built these fields primarily for maize cultivation, even if highly drought-adapted varieties were grown. This assessment is based on the relatively high water and nutrient requirements of maize. From a geomorphic standpoint (namely, the small catchment size), it appears that runoff water was of secondary importance to the farmers compared to the mulching effect provided by the agricultural rock alignments and piles. Instead, it seems more likely that annual desert succulents, especially agave or possibly even cacti or yucca, were cultivated, possibly entailing a dual- or multiple-cropping system.

Colonies of *Agave murpheyi*, a domesticated species of agave, have been identified in many valleys (e.g., Tonto Basin, and the lower Verde, Agua Fria, and New river valleys) of central Arizona (Hodgson et al. 1989, Homburg 1997). These colonies are the most direct evidence of late prehistoric agave cultivation in the state. Abundant, though less direct evidence, of agave cultivation has been found in southern Arizona, in the form of charred agave remains from roasting pits next to rock pile fields and the presence of stone tools thought to reflect agave processing activities (Fish 1993, Fish et al. 1992, Fish et al. 1985). *A. murpheyi* colonies are usually found growing in cobbly soils on gentle, southwest-facing slopes of alluvial fans and river terraces. *A. murpheyi* only reproduces vegetatively from clonal offshoots and bulbils, rather than from seed, so it requires human aid to colonize new areas. Because these colonies are invariably found with traces of agricultural activity (e.g., rock piles and alignments, terraces, tabular knives, and steep-edged scraping tools), often associated with Classic Period Hohokam or Salado sites, they are considered living remnants of ancient farming activity (Hodgson et al. 1989). Tabular knives, often referred to as agave knives, and large primary flakes that may have served as cutting implements are common at the SGF.

No such colonies have been found in the Safford Basin. Because the Safford Basin receives significantly less precipitation than the Transition Zone of Central Arizona where these colonies are widespread, it is distinctly possible that such colonies once existed in the Safford Basin but failed to survive to the present without human aid. Alternatively, they may have been completely harvested by later occupants. From the standpoint of the soils and climate, agave is a likely candidate for cultivation in the SGF, because it thrives in cobbly, calcareous, droughty soils, even in soils with a low nutrient status and ones in hilly terrain that support little other vegetation.

SUMMARY AND CONCLUSIONS

Soil properties associated with gridded rock alignments, rock piles, and terraces were evaluated in Locality 1 of the SGF. This soil investigation was aimed at documenting soil properties, assessing agricultural productivity, and speculating about which crops may have been cultivated. Soils consist chiefly of gravelly loams and clay loams dominated by shallow petrocalcic or argillic horizons, both of which strongly impede or block water infiltration and hold moisture in the rooting zone within or above these zones. Compared to uncultivated soils, agricultural soils at the SGF generally have reduced pH levels, which would have been beneficial for crop production due to increased plant availability for many essential nutrients. Nitrogen and available phosphorus content is consistently higher in the gridded and terrace alignments soils, and upper terrace positions immediately below terrace alignments. If these elevated nutrient levels are not the result of changes since field abandonment, then cultivation is associated with improved soil fertility. Compared to uncultivated controls, cultivated soils tend to have similar or slightly reduced organic carbon levels. Importantly, the grid alignment soils have significantly elevated organic carbon, nitrogen, and available phosphorus levels compared to the grid interiors. The precise cause of these chemical soil differences is uncertain; they may reflect either direct cultivation effects or post-cultivation vegetation associations with agricultural features. Bulk density tests do not indicate that ancient cultivation practices caused soil compaction. In short, there is no indication that ancient farming activity seriously degraded the soil. Overall, soil nutrient levels are sufficient to have supported maize agriculture, but the thin soils, high temperatures, low rainfall, and low runoff throughout most landscape positions of the field suggest that crops such as agave or other drought-tolerant plants were likely the focus of agricultural production.

Our soil investigation of the SGF is far from exhaustive, given that it was mainly limited to a relatively small sample in Locality 1. Future soil studies should expand the scope of soil sampling to include other parts of the field, especially the large gridded fields and terraces east of Peck Wash. Another potentially productive avenue of research would be to compile detailed soil mapping data on the distribution and depth of petrocalcic and argillic horizons, and then evaluate the relationship between these three-dimensional soil bodies and spatial patterning of different types of agricultural features.

REFERENCES

Alderfer, R. B. and F. G. Merkle
1943 The Comparative Effects of Surface Application Versus Incorporation of Various Mulching Materials on Structure, Permeability, Runoff, and Other Soil Properties. *Soil Science Society of America Proceedings* 8: 79-86.

Arrhenius, O.
1963 Investigation of Soil from Old Indian Sites. *Ethnos* 28: 122-136.

Baize, D.
1993 *Soil Science Analysis: A Guide to Current Use*. John Wiley & Sons. Chichester.

Barbour, M. G., G. Cunningham, W. C. Oechel, and S. A. Bamberg
1977 Growth and Development, Form and Function. In *Creosote Bush: Biology and Chemistry of Larrea in New World Deserts*, edited by T. J. Mabry, J. H. Hunziker and D. R. Difeo, pp. 48-91. Dowden, Hutchinson, & Ross, Inc., Stroudsburg, Pennsylvania

Benoit, G. R. and D. Kirkham
1963 The Effect of Soil Surface Conditions on Evaporation of Soil Water. *Soil Science Society of America Proceedings* 27: 495-498.

Berlin, G. L., D. E. Salas, and P. R. Geib
1990 A Prehistoric Sinagua Agricultural Site in the Ashfall Zone of Sunset Crater, Arizona. *Journal of Field Archaeology* 17: 1-16.

Blake, G. R. and K. H. Hartge
1986 Bulk Density. In *Methods of Soil Analysis. Physical and Mineralogical Methods* (2nd edition), edited by A. Klute, pp. 363-375. Agronomy Monography No. 9, Part 2. American Society of Agronomy and Soil Science Society of America, Madison.

Brady, N. C. and R. R. Weil
1999 *The Nature and Properties of Soils*. Prentice Hall, Upper Saddle River, New Jersey.

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

Choriki, R. T., J. C. Hide, S. L. Krall, and B. L. Brownet
1964 Rock and Gravel Mulch Aid in Moisture Storage. *Crops and Soil* 16(9): 24.

Ciolek-Torrello, R. and J. R. Welch (editors)
1994 *Changing Land-use Practices in the Tonto Basin*. Statistical Research Technical Series No. 28, Tucson.

Cordell, L. S.
1998 *Archaeology of the Southwest*. New York, Academic Press.

Dick, W. A. and M. A. Tabatabai
1977 An Alkaline Oxidation Method for Determination of Total Phosphorus in Soils. *Soil Science Society of America Journal* 41(3): 511-514.

Doerge, T. A.
1985 *A Summary of Soil Test Information for Arizona's Surface Agricultural Soils: 1965-1984*. Tucson, Department of Soil and Water Science, University of Arizona.

Doolittle, W. E.
1984 Cabeza de Vaca's Land of Maize: An Assessment of Its Agriculture. *Journal of Historical Geography* 10: 246-262.

1988 *Pre-Hispanic Occupance in the Valley of Sonora, Mexico: Archaeological Confirmation of Early Spanish Reports*. The University of Arizona Press, Tucson.

1998 Innovation and Diffusion of Sand- and Gravel-Mulch Agriculture in the American Southwest: A Product of the Eruption of Sunset Crater. *Quaternaire* 9(1): 61-69.

Dorn, R. I., D. B. Bamforth, T. A. Cahill, J. C. Dohrenwend, B. D. Turrin, D. J. Donahue, A. J. T. Jull, A. Long, M. E. Macko, E. B. Weil, D. H. Whitney, and T. H. Zabel
1986 Cation-ratio and Accelerator Radiocarbon Dating of Rock Varnish on Mojave Artifacts and Landforms. *Science*: 1472-1474.

Dorn, R. I. and M. J. DeNiro
1984 Stable Carbon Isotope Ratios of Rock Varnish Organic Matter: A New Paleoenvironmental Indicator. *Science* 227(1472:1474).

Dorn, R. I. and T. M. Oberlander
1981 Microbial Origin of Desert Varnish. *Science* 213: 1245-1247.

Dregne, H. E.
1963 Soils of the Arid West. In *Aridity and Man: The Challenge of the Arid Lands in the United States*, by C. Hodge and P. C. Duisberg, pp. 215-238. American Association for the Advancement of Science, Washington.

Elvidge, C. D.
1982 A Reexamination of the Rate of Desert Varnish Formation Reported South of Barstow, California. *Earth Surface Processes and Landforms* 7: 345-348.

Evenari, M., L. Shanan, and N. H. Tadmor
1982 *The Negev: The Challenge of a Desert.* Harvard University Press, Cambridge.

Fairbourn, M. D.
1973 Effect of Gravl Mulch on Crop Yields. *Agronomy Journal* 65: 925-928.

Fireman, M. and C. H. Wadleigh
1951 A Statistical Study of the Relation Between pH and the Exchangeable-sodium Percentage of Western Soils. *Soil Science* 71: 273-285.

Fish, S. K.
1993 *Agriculture and Society in Arid Lands.* Department of Arid Lands Resource Sciences, The University of Arizona, Tucson.

1995 Mixed Agricultural Technologies in Southern Arizona and Their Implications. *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture.* H. W. Toll. New Mexico Archaeological Council, Albuquerque.

Fish, S. K. and P. R. Fish (editors)
1984 *Prehistoric Agricultural Strategies in the Southwest.* Arizona State University, Tempe.

Fish, S. K., P. R. Fish, and J. Madsen (editors)
1992 *The Marana Community in the Hohokam World.* Anthropological Papers of the University of Arizona No. 56. The University of Arizona Press, Tucson.

Fuller, W. H.
1975 *Soils of the Desert Southwest.* The University of Arizona Press, Tucson.

Fuller, W. H. and H. E. Ray
1965 *Basic Concepts of Nitrogen, Phosphorus, and Potassium in Calcareous Soils.* The University of Arizona, Tucson.

Gallegos, R. A. and H. C. Monger
1997 Phytogenic Carbonate, Desert Shrubs, and Stable Carbon Isotopes. *1998 Annual Meeting Abstracts.* Baltimore, Soil Science Society of America, Baltimore.

Gee, G. W., and J. W. Bauder
1986 Particle-size Analysis. In *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods.* Edited by A. Klute, pp. 383-411. Agronomy Monography No. 9. American Society of Agronomy and Soil Science Society of America, Madison.

Gelderman, F. W.
1970 *Soil Survey of the Safford Area, Arizona.* U. S. Department of Agriculture, Soil Conservation Service, Washington.

Gile, L. H., J. W. Hawley, and R. B. Grossman
1981 *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico: Guidebook to the Desert Project.* New Mexico Bureau of Mines and Mineral Resources, Socorro.

Gile, L. H., F. F. Peterson, and R. B. Grossman
1966 Morphological and Genetic Sequences of Carbonate Accumulation in Desert Soils. *Soil Science* 101(347-360).

Gilman, P. L. and P. Sherman
1975 *An Archaeological Survey of the Graham-Curtis Project: Phase II.* The University of Arizona Press Tucson.

Glinski, J. and J. Lipiec
1990 *Soil Physical Conditions and Plant Roots.* Boca Ratan, Florida, CRC Press.

Hack, J. T.
1942 *The Changing Physical Environment of the Hopi Indians of Arizona.* Papers of the Peabody Museum of American Archaeology and Ethnography No. 35, Cambridge, Peabody Museum.

Hausenbuiller, R. L.

Glinski, J. and J. Lipiec
1990 *Soil Physical Conditions and Plant Roots.* Boca Ratan, Florida, CRC Press.

Hack, J. T.
1942 *The Changing Physical Environment of the Hopi Indians of Arizona.* Papers of the Peabody Museum of American Archaeology and Ethnography No. 35, Cambridge, Peabody Museum.

Hausenbuiller, R. L.
1972 *Soil Science: Principles and Practices.* Wm. C. Brown Company Publishers, Dubuque, Iowa.

Heinonen, R.
1985 *Soil Management and Crop Water Supply.* University of Agricultural Sciences. Uppsala, Sweden.

Hendricks, D. M.
1985 *Arizona Soils.* College of Agriculture, The University of Arizona, Tucson

Hodgson, W., G. Nabhan, and L. Ecker
1989 Prehistoric Fields in Central Arizona: Conserving Rediscovered Agave Cultivars. *Agave* 3(3): 9-11.

Homburg, J. A.
1994 Soil Fertility in the Tonto Basin. In *Changing Land-use Practices in the Tonto Basin,* Vol. 3: Field Study, edited by R. Ciolek-Torrello and J. R. Welch; pp. 253-295, Statistical Research Technical Series 28, Tucson.

1997 Prehistoric Dryland Agricultural Fields of the Lower Verde. In *Vanishing River: Landscapes and Lives of the Lower Verde Valley: The Lower Verde Archaeological Project, Vol. 2: Agricultural, Subsistence, and Environmental Studies,* edited by J. A. Homburg and R. Ciolek-Torrello, pp. 103-106, SRI Press, Tucson.

Homburg, J. A. and J. A. Sandor
1997 An Agronomic Study of Two Classic Period Agricultural Fields in the Horseshoe Basin. In *Vanishing River: Landscapes and Lives of the Lower Verde Valley. The Lower Verde Archaeological Project. Vol. 2: Agricultural, Subsistence, and Environmental Studies,* edited by J. A. Homburg and R. Ciolek-Torrello pp. 127-148, SRI Press, Tucson.

Hough, W.

1907 *Antiquities of the Upper Gila and Salt River Valleys in Arizona and New Mexico.* Smithsonian Institution, Washington,

Jeffrey, D. W.

1987 *Soil-Plant Relationships: An Ecological Approach.* Timber Press, Portland.

Jenny, H.

1941 *Factors of Soil Formation.* New York, McGraw-Hill.

Lang, R. W.

1981 *A Prehistoric Pueblo Garden Plot on the Rio Ojo Caliente, Rio Arriba County, New Mexico: Ojo Caliente Site 7, Features 1-2.* Santa Fe, School of American Research.

Lightfoot, D. R.

1990 *The Prehistoric Pebble-mulched Fields of the Galisteo Anasazi: Agricultural Innovation and Adaptation to Environment.* PhD. Dissertation, Department of Geography, University of Colorado, Boulder.

1993a The Landscape Context of Anasazi Pebble-Mulched Fields in the Galisteo Basin, Northern New Mexico. *Geoarchaeology* 8(5): 349-370.

1993b The Cultural Ecology of Puebloan Pebble-Mulch Gardens. *Human Ecology* 21(2): 115-143.

1994 Morphology and Ecology of Lithic-Mulch Agriculture. *The Geographical Review* 84(2): 172-185.

1996 The Nature, History, and Distribution of Lithic Mulch Agriculture: An Ancient Technique of Dryland Agriculture. *The Agricultural History Review* 44(2): 206-222.

Lightfoot, D. R. and F. W. Eddy

1994 The Agricultural Utility of Lithic-Mulch Gardens: Past and Present. *Geojournal* 34(4): 425-437.

1995 The Construction and Configuration of Anasazi Pebble-Mulch Gardens in the Northern Rio Grande. *American Antiquity* 60(3): 459-470.

Loomis, R. S. and D. J. Connor

1992 *Crop Ecology: Productivity and Management in Agricultural Systems.* Cambridge University Press, Cambridge.

Ludwig, J. A.
1987 Primary Productivity in Arid Lands: Myths and Realities. *Journal of Arid Environments* 13: 1-7.

Machette, M. N.
1965 Calcic Soils of the Southwestern United States. In *Soils and Quaternary Geology of The Southwestern United States*, edited by D. L. Weide, pp. 1-22. The Geological Society of America, American Society of Agronomy, and Soil Science Society of America, Boulder and Madison.

Masse, W. B.
1979 An Intensive Survey of Prehistoric Dry Farming Systems Near Tumamoc Hill in Tucson, Arizona. *The Kiva* 45: 141-186.

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

McLean, E. O.
1982 Soil pH and Lime Requirements. In *Methods of Soil Analysis. Chemical and Microbiological Properties*, edited by A. L. Page, R. H. Miller, and D. R. Keeney, pp.199-222. Agronomy Monograph No. 9, Part 2. American Society of Agronomy and Soil Science Society of America, Madison.

Mehuys, G. R., L. H. Stolzy, J. Letey, and L. V. Weeks
1975 Effect of Stones on the Hydraulic Conductivity of Relatively Dry Desert Soils. *Soil Science Society of America Proceedings* 39: 37-42.

Murphy, C. H.
1984 *Handbook of Particle Sampling and Analysis Methods*. Verlag Chemie International, Dearfield Beach, Florida.

Nabhan, G. P.
1983 *Papago Fields: Arid Lands Ethnobotany and Agricultural Ecology. Department of Arid Lands Resource Sciences*. PhD. Dissertation, Department of Arid Lands Resource Sciences, The University of Arizona, Tucson.

1984 Soil Fertility Renewal and Water Harvesting in Sonoran Desert Agriculture: The Papago Example. *Arid Lands Newsletter* 20: 21-28.

National Soil Survey Center
1996 *Soil Survey Laboratory Methods Manual.* Lincoln, Nebraska, U. S. Department of Agriculture, Natural Resources Conservation Service.

Nelson, D. W. and L. E. Sommers
1982 Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis. Chemical and Microbiological Methods*, edited by A. L. Page, R. H. Miller and D. R. Keeney, pp. 539-579. Agronomy Monograph No. 9, Part 2, American Society of Agronomy and Soil Science Society of America, Madison.

Olsen, S. R. and L. E. Sommers
1982 Phosphorus. *Methods of Soil Analysis. Chemical and Microbiological Methods.* A. L. Page, R. H. Miller and D. R. Keeney, pp. 403-430. Agronomy Monograph No. 9, Part 2, American Society of Agronomy and Soil Science Society of America, Madison.

Rankin, A. G. and K. L. Katzer
1989 Agricultural Systems in the ACS Waddel Project Area. In *Settlement, Subsistence, and Specialization in the Northern Periphery: The Waddell Project*, edited by M. Green. Phoenix, pp. 981-1020. Archaeological Consulting Services, Ltd., Phoenix.

Rommey, E. M., A. Wallace, and R. B. Hunter
1978 Plant Response to Nitrogen Fertilization in the Northern Mohave Desert and Its Relation to Water Manipulation. In *Nitrogen in Desert Ecosystems*, edited by N. E. West and Skujins, pp. 232-242Stroudsburg, Pennsylvania.

Russell, F.
1908 *The Pima Indians.* 26th Annual Report of the Bureau of American Ethnology to the Secretary of the Smithsonian Institution, Washington.

Saini, G. R. and A. A. MacLean
1967 The Effect of Stones on Potato Yield, Soil Temperature, and Moisture. *American Potato Journal* 44: 209-213.

Sanders, W. T.
1992 Comments by William T. Sanders. In "Summary and Critique" by B.L. Turner II and W. T. Sanders. *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica.* T. W. Killion. Tuscaloosa, The University of Alabama Press: 263-284.

Sandor, J. A.
1983 *Soils at Prehistoric Agricultural Terracing Sites in New Mexico*. Department of Soil Science. PhD. Dissertation, Department of Soil Science, University of California, Berkeley.

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

Sandor, J. A. and P. L. Gersper
1988 Evaluation of Soil Fertility in Some Prehistoric Agricultural Terraces in New Mexico. *Agronomy Journal* 80: 846-850.

Sandor, J. A., P. L. Gersper, and J. W. Hawley
1986 Soils and Prehistoric Agricultural Terracing Sites in New Mexico: I. Site Placement, Soil Morphology, and Classification: II. Organic Matter and Bulk Density Changes. Soils at Prehistoric Agricultural Terracing Sites in New Mexico: III. Phosphorus, Selected Micronutrients, and pH. *Soil Science Society of America Journal* 50: 173-180.

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

Sandor, J. A. and J. A. Homburg
1997 Soils and Prehistoric Agricultural Sites on Piedmont Slopes Near Paquime, Chihuahua, Mexico. Draft report for National Geographic project, submitted to Paul Minnis, Department of Anthropology, University of Oklahoma, Norman.

Sellers, W. D. and R. H. Hill
1974 *Arizona Climate: 1931-1972*. The University of Arizona Press, Tucson.

Soil Science Society of America
1987 *Glossary of Soil Science Terms*. Soil Science Society of America, Madison.

Soil Survey Staff
1993 *Soil Survey Manual*. U. S. Department of Agriculture, United States Government Printing Office, Washington.

1998 *Keys to Soil Taxonomy*. U. S. Department of Agriculture, Natural Resources Conservation Service, Washington.

1999 *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys.* U. S. Department of Agriculture, United States Government Printing Office. Washington.

Solbrig, O. T.
1977 The Adaptive Strategies of *Larrea.* In *Creosote Bush: Biology and Chemistry of Larrea in New World Deserts*, edited by T. J. Mabry, J. H. Hunziker and D. R. Difeo, pp. 1-9. Dowden, Hutchinson, & Ross, Stroudsburg, Pennsylvania.

Stevenson, F. J.
1982 *Nitrogen in Agricultural Soils.* American Society of Agronomy, Madison.

Stewart, G. R.
1939 Conservation Practices in Primitive Agriculture of the Southwest. *Soil Conservation* 5: 112-115, 131.

Stewart, G. R.
1940 Conservation in Pueblo Agriculture: I. Primitive Practices. *The Scientific Monthly* 51: 201-220.

Sutton, J. E. G.
1969 "Ancient Civilizations" and Modern Agricultural Systems in the Southern Highlands of Tanzania. *Azania* 4: 1-13.

1978 Engaruka and Its Waters. *Azania* 4: 37-70.

1990 *A Thousand Years of East Africa.* British Institute in Eastern Africa, Nairobi.

Tisdale, S., W. L. Nelson, and J. D. Beaton
1985 *Soil Fertility and Fertilizers.* Macmillan Publishing Company, New York.

Toll, H. W. (editor)
1995 *Soil, Water, Biology, and Belief in Prehistoric and Traditional Southwestern Agriculture.* Special Publication No. 2. New Mexico Archaeological Council, Albuquerque.

Vanderpot, R.
1992 *Rockpile Areas and Other Specialized Activity Sites on the Gila River Terrace: An Appraisal of Hohokam Auxiliary Agricultural Strategies Near Florence, Arizona.* Statistical Research Technical Series 32, Tucson.

Ware, J. A. and M. Mensel
1992 *The Ojo Caliente Project: Archaeological Test Excavations and A Data Recovery Plan for Cultural Resources Along U. S. 285, Rio Arriba County, New Mexico*. Museum of New Mexico, Santa Fe.

Wild, A.
1993 *Soils and Environment: An Introduction*. Cambridge University Press, Cambridge.

Woodbury, R. B.
1961 *Prehistoric Agriculture at Point of Pines, Arizona*. Society for American Archaeology, Salt Lake City.

Woosely, A. I.
1980 Agricultural Diversity in the Prehistoric Southwest. *The Kiva* 45: 317-335.

Yaalon, D. H.
1957 Problems of Soil Testing on Calcareous Soils. *Plant and Soil* 8: 275-288.

Young, H. M., Jr.
1982 *No-Tillage Farming*. No-Till Farmer, Brookfield, Wisconsin.

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CHAPTER 3
ANTHROPOGENIC INFLUENCES ON ZUNI AGRICULTURAL SOILS

A paper to be submitted to *Journal of Arid Environments*

Jeffrey A. Homburg, Jonathan A. Sandor, and Jay B. Norton

ABSTRACT

The Zuni and other Native American groups of the semiarid Southwest U. S. have successfully cultivated maize and other crops for over two millennia without using formal irrigation or artificial fertilizers. Zuni fields are among the oldest, more or less continuously, cultivated areas in the United States. Traditional Zuni agriculture is based on a runoff farming system, whereby storm water flow and organic-rich sediment is captured from watersheds and directed onto agricultural fields. Long-term agricultural soils of semiarid regions of the Southwest, including those of Zuni fields, are well suited for agronomic research because soil formation (e.g., weathering, leaching, and illuviation) proceeds much more slowly in deserts than in humid environments, so soil changes caused by cultivation practices tend to persist and be detectable for long periods. We conducted a study to compare soil properties associated with cultivated, abandoned, and uncultivated fields. This research was aimed at documenting and evaluating the long-term effects of cultivation on soil properties of Zuni agricultural runoff soils.

Field and lab results indicate that tillage in recent decades has altered some soil properties but there is no clear indication that agricultural soils are degraded. Paired

cultivated soils are 7.6% higher in bulk density on average and they have greater massive structure and reduced granularity. By contrast, unpaired cultivated soils are only 3.5% higher in bulk density, which is not enough to indicate degradation, especially given the friable to very friable consistence of topsoils. Higher pH levels in the paired and unpaired cultivated soils were found, caused by greater deposition of calcareous sediment from the upper watersheds. No consistent differences in organic C, N, and available and total P were identified in the statistical analysis of paired fields, which further suggests there is no indication that cultivated soiis are degraded. No statistically significant differences were identified in soils from a much larger data set of unpaired cultivated, abandoned, and uncultivated treatments, but significant differences in pH and bulk density were found among the three study areas in the eastern part of the Zuni Reservation. Because of the much greater sample size of unpaired fields, the lack of significant identifiable changes caused by cultivation strongly indicates that Zuni agricultural runoff soils are not degraded. This assessment supports the perception of Zuni farmers that long-term cultivation has not caused a decline in agricultural productivity.

"Take the best of the old Indian ways -- always keep them. They have been proven for thousands of years. Do not let them die." (Sitting Bull (1834-1890) Hunkpapa Lakota, South Dakota).

INTRODUCTION

Most assessments of cultivation effects on soil productivity rely on observations obtained over brief periods, often less than five years and rarely exceeding 100 years (Fenton et al. 1999). Because of such limited time perspective on anthropogenic soil changes, it is peculiar that so few agronomists and soil scientists have studied the oldest American farming systems, those of American Indians. To help fill this data gap, we conducted a soil study of an American Indian agricultural system in a semiarid region of west-central New Mexico (Figure 3.1). Zuni fields are among the oldest identifiable agricultural fields in the United States, so this project provided a unique opportunity to document and evaluate soil properties associated with long-term agriculture practices. Agriculture has been practiced in the Zuni homeland for over two millennia, so there is little question that their traditional cropping system is one that is highly sustainable. It is unclear, however, how plowing (which was not practiced by ancient farmers) over the last century has affected soil properties, and that is the focus of this study. Agronomists and soil scientists with expertise in soil biology, physics, and morphology from various academic and private institutions collaborated with land managers and farmers from the Zuni Conservation Project to conduct this scientific investigation, sponsored by the National Science Foundation (NSF).

Overcoming low water availability is usually viewed as the major hurdle to achieving agricultural sustainability in the semiarid Southwest, which contrasts sharply with humid regions where soil fertility maintenance is the main limiting factor (Dregne 1963: 219, Sanders 1992: 283). Soil fertility is also an important concern for farming systems in the Southwest, and productivity is not limited by water alone (Ludwig 1987). Nitrogen deficiency is so common in desert soils that its effect in limiting agricultural production is almost as great as water availability (Rommey et al. 1978; Nabhan 1983; Nabhan 1984; Sandor and Gersper 1988). Cultivation of crops with high nutrient requirements, such as maize, heightens

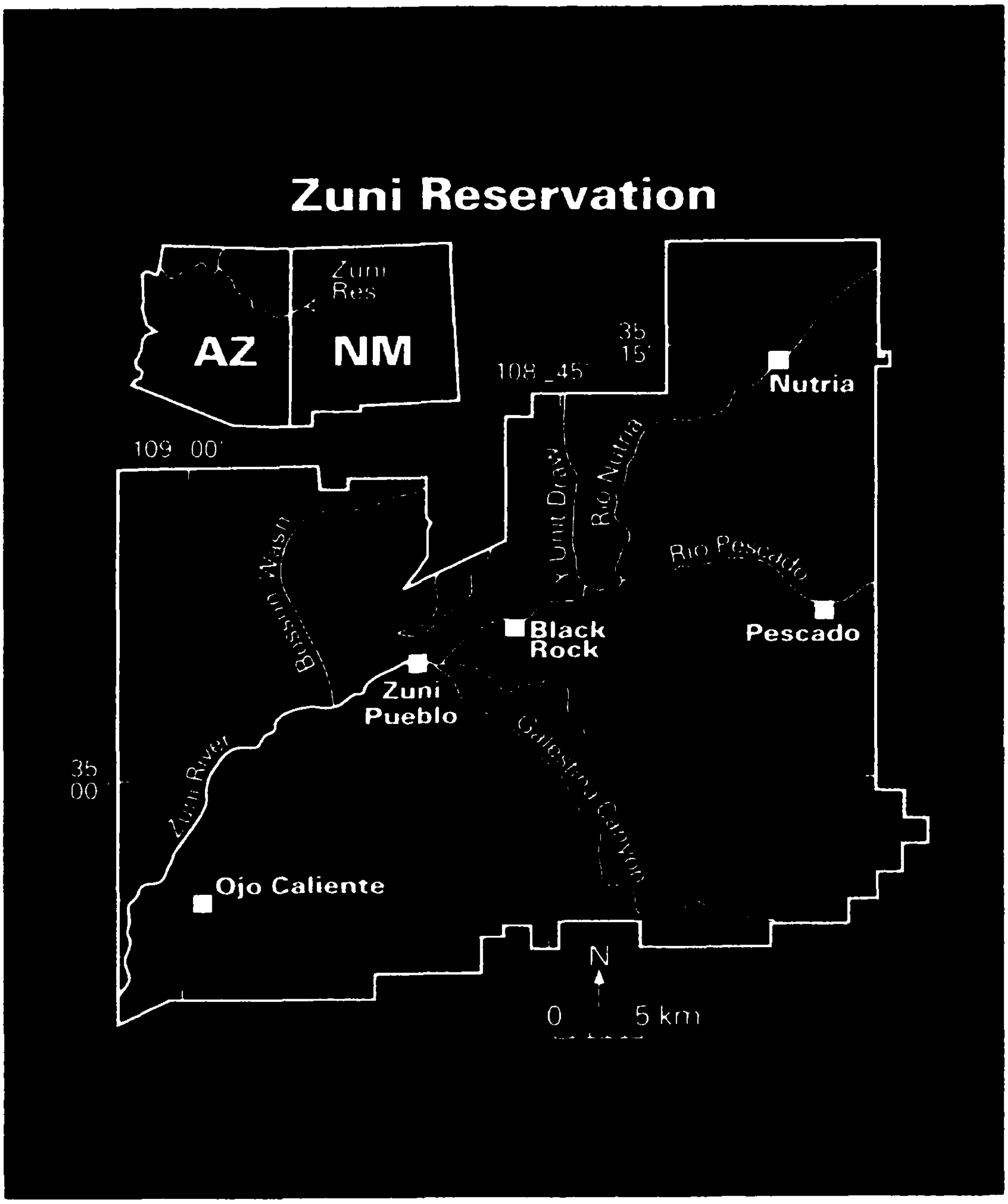


Figure 3.1. Location of Zuni Reservation.

this problem by depleting already low nitrogen stores (Stevenson 1982; Doolittle 1984; Loomis and Connor 1992: Fig. 12.1).

Research objectives of our Zuni agricultural soil study are as follows: (1) characterize the chemical and physical properties of soils for runoff agriculture; (2) identify and assess soil and geomorphic factors important to the functioning of Zuni runoff fields; (3) evaluate if long-term cultivation has altered the quality of Zuni agricultural soils. To measure the effects of cultivation on soil quality, chemical and physical properties of soils from modern Zuni fields were analyzed at two spatial scales: (1) sampling at three paired (intensive) cultivated and uncultivated fields; and (2) sampling at 29 unpaired (extensive) cultivated, abandoned, and uncultivated fields. These soil-sampling areas are depicted in Figure 3.2.

We attempted to hold non-anthropogenic soil-forming factors reasonably constant (especially climate, topography, and geology) by focusing our soil-sampling effort on similar elevations, landscape positions, and geologic contexts. Soil samples were collected from alluvial fans and a few footslopes, mainly at elevations of about 2070 m and in watersheds smaller than about 150 hectares. We concentrated our sampling effort on soil map units of the Hosta series, a widespread soil where many runoff fields are located in the eastern part of the reservation where our study was conducted.

Two intensive fields were selected near historic farming villages, one near Lower Nutria and the other near Pescado. Archival records indicate that both areas were used extensively for agriculture from about the turn of the last century to about World War II. Agricultural fields along Pescado Wash and the alluvial fans flanking it are depicted in a mid-

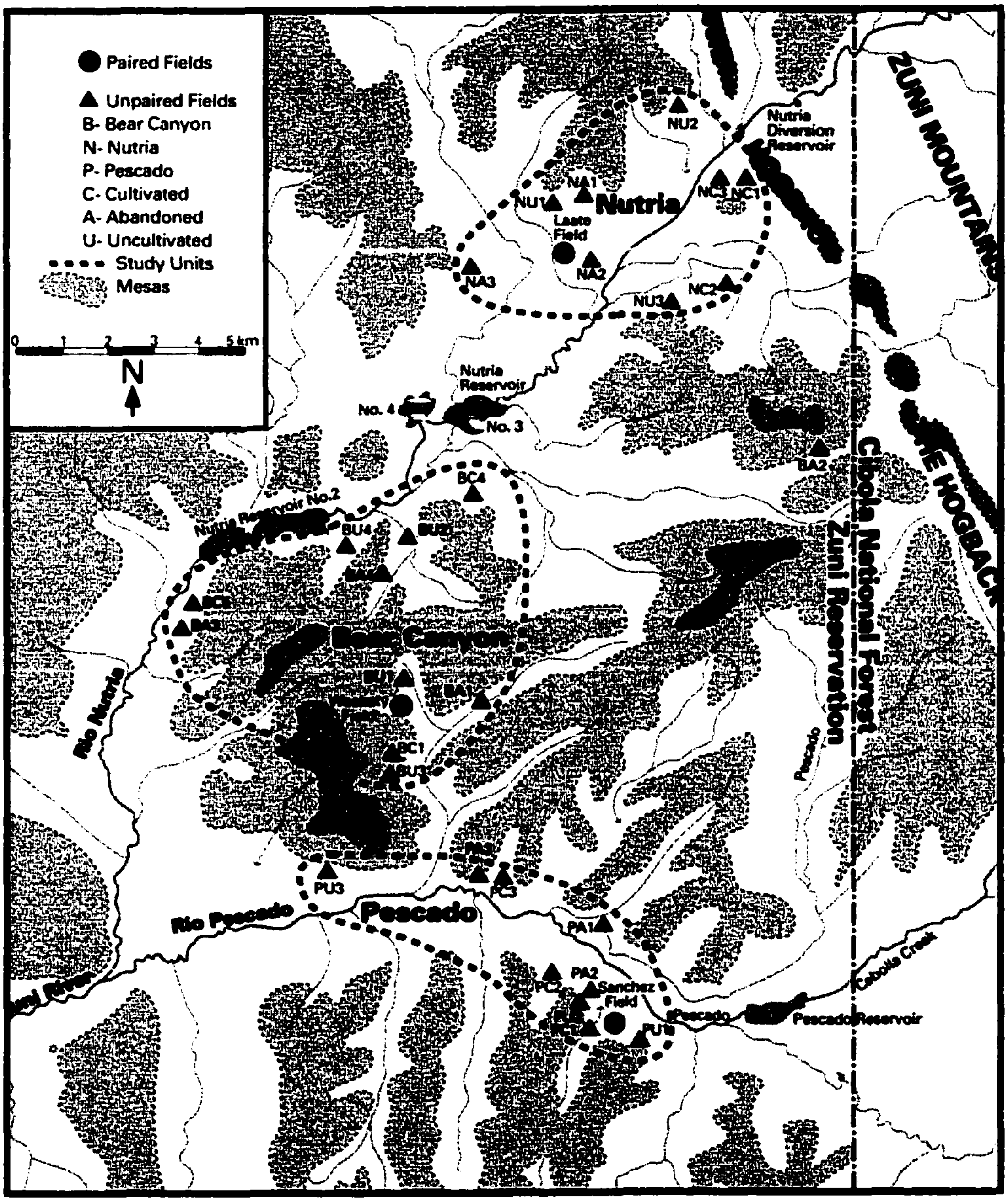


Figure 3.2. Location of paired (intensive) and unpaired (extensive) fields.

1930s aerial photograph (Figure 3.3), when farming activity was widespread across Zuni farming districts. The third field is in an area identified by some local farmers as Bear Canyon. We refer to the intensive fields in the Nutria, Pescado, and Bear Canyon study areas as the Laate, Sanchez, and Weekoty fields, respectively. These fields are named for the farmers who most recently cultivated them. The 29 extensive fields are roughly evenly divided between the Nutria, Pescado, and Bear Canyon study areas, and between cultivated, abandoned, and uncultivated land. Cultivated fields are defined as those that were either currently farmed or recently left fallow within the last decade, and have been plowed mechanically since about World War II. Abandoned fields include fields that were tilled mainly by horse-drawn plows through the early 1940s, but have since been left fallow. Uncultivated fields are ones lacking archival evidence of farming activity. It is important to note that most of the fields sampled, even those defined for the purpose of this study as uncultivated, were in fact farmed prehistorically. Archaeological features and artifacts were commonly encountered during the course of fieldwork, often within 100 m of our soil sampling areas, and these cultural remains are a clear indication of ancient farming. Because of variability in the timing and intensity of ancient farming in the fields we sampled, this activity has a potential confounding effect in our analysis of soil changes over the last century. The presence of these ancient fields, however, supports our contention that the uncultivated fields we selected for analysis are good reference samples for comparison; that is, they lack evidence of farming over the last century but they are in similar landscape positions suitable for agriculture because they actually have been cultivated. To obtain information on ancient farming, we recorded archaeological sites, which involved making

Figure 3.3. Photograph of 1930s agricultural fields (from the Soil Conservation Service).

surface observations of ceramic and lithic artifacts. Archaeological features included stone rubble from field houses and farmsteads, stone granaries sealed with a mud mortar, and stone alignments built to slow runoff water and reduce erosion. Decorated pottery indicates that runoff farming was especially widespread from about A.D. 1050 to 1150 (Pueblo II period). It is likely that traces of prehistoric farming activity are also buried in the alluvium of our soil sampling loci.

Some research was conducted on Zuni agricultural soils prior to the start of this NSF project. Roman Pawluk (1995) conducted interviews of Zuni farmers in 1991 to document their knowledge and concepts of agricultural soils and organic-rich sediment. Interestingly, Pawluk learned of a Zuni term, *tanayan sowe* (which means "tree soil"). This concept clearly shows that Zuni farmers recognize the crucial role played by organic-rich sediments in nutrient renewal of agricultural soils. Later, during the course of fieldwork on our NSF project, we started thinking of this material as "walking compost," consisting of patchy concentrations of organic debris that decomposes as it is carried toward agricultural fields below by runoff from episodic storm events.

Soils, hydrology, and vegetation associations of the Sanchez field and watershed were investigated by Jay Norton (Norton 1996, Norton et al. 1998) as part of his Master's research at Iowa State University. Norton's thesis incorporated field soil data collected by Jonathan A. Sandor in 1991 in this same field. Watersheds were a logical scale of analysis for Norton's study of agricultural landscapes and soils (see Lowrance 1992). Fields on alluvial fans and the watersheds that feed them form a natural agroecological pair, and this same analytical approach was continued in the present NSF project. Norton's soil testing data are included within the larger data set presented here in this paper. Norton's study demonstrated the importance of small watersheds in supplying water and nutrients to Zuni fields (Figures 3.4 and 3.5), which is consistent with the findings of previous studies of runoff farming in the semiarid Southwest (Bryan 1929, Hack 1942, McGee 1895, Nabhan 1984, Nabhan 1979, Nabhan 1983, Nabhan 1986a, Nabhan 1986b); Stewart 1939; Stewart 1940) and other deserts around the world (Boers and Ben-Asher 1982, Bruins 1986, Bruins 1990, Bruins et al. 1987, Cohen et al. 1995, Evenari et al. 1982, Kowsar 1991, Lavee et al. 1997, Niemeijer 1998, Parr 1943). Norton is continuing his work on Zuni runoff farming at the School of Forestry at the University of Montana, with his doctoral research focused on N mineralization in Zuni fields. He is also studying the hydrology of the Weekoty watershed and spearheading efforts to revitalize Zuni runoff farming.

BACKGROUND DISCUSSION

Background on the Zuni and Runoff Farming

The Zuni, who now number over 9000, are one of the Western Puebloan tribes of the Southwest. They have a close affinity with the Hopi, another of the western Puebloan tribes, who live further west in Arizona. The traditional homeland of the Zuni extends over a broad region in west-central New Mexico and east-central Arizona, extending far outside of the reservation where they now live (Ferguson and Hart 1985). Zuni and other American Indian groups of the semiarid Southwest have a long tradition of runoff farming, and it is significant that even today their system does not rely on artificial fertilizers. Instead, their fields are

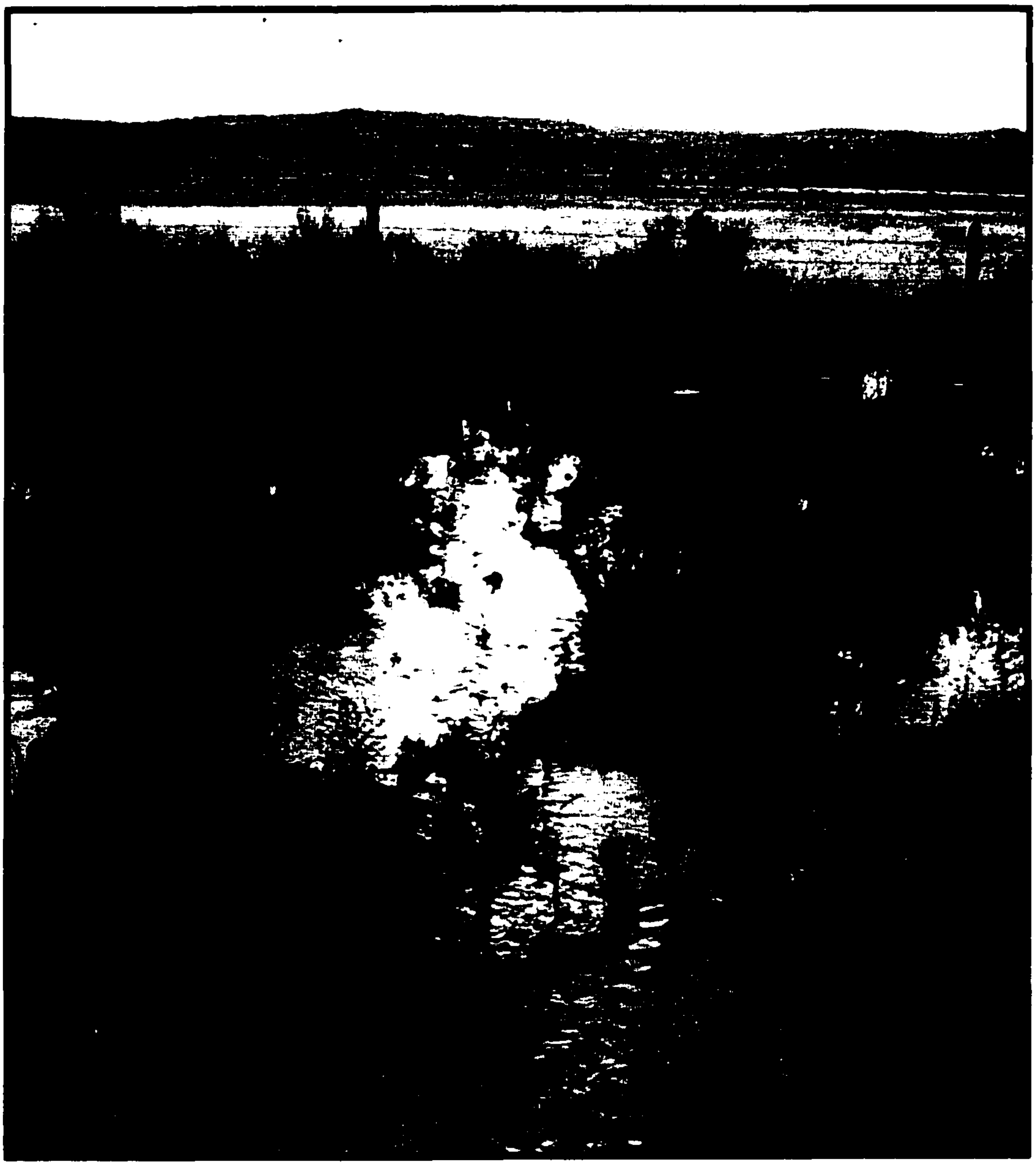


Figure 3.4. Floodwater draining into a field during a runoff event.

Figure 3.5. Organic-rich sediment delivered to alluvial fan by runoff.

fertilized with organic-rich sediments carried in runoff water. This organic-rich debris drains from upper watersheds and is deposited throughout alluvial fan surfaces, especially on footslopes.

Runoff farming is an agricultural system that involves capturing storm water flow and sediment from watersheds and directing it onto agricultural fields (see Figures 3.4 and 3.5). This type of agricultural system is a case whereby farmers take advantage of natural erosion in the watershed. Earthen berms, rock alignments, wooden dams, and shallow ditches are commonly built to control erosion and divert runoff across fields for crop use. Over 100 years ago, Frank Cushing, an early anthropologist, was the first to document how effective Zuni techniques were at spreading runoff water and organic-rich sediment throughout an agricultural field (Cushing 1979; reprint of selected writings first published in 1884). Zuni runoff fields are placed on alluvial fans and foot slopes in valley margin and canyon settings. These landforms are productive settings for agriculture because: (1) runoff water and nutrients are naturally concentrated on these landforms; (2) the growing season is extended because cold air drainage effects are reduced compared to valley bottoms; and (3) potential salinization effects are reduced compared to irrigated fields on valley floors.

Digging sticks, the traditional farming implement, were replaced by horse-drawn plows around the turn-of-the-century and later by tractor-drawn plows in the 1940s and 1950s. Today, agricultural fields are mainly watered by irrigation, but runoff farming is still in practice. The amount of land devoted to agricultural production has declined over the last few decades, but farming continues to play an integral role in Zuni society. The Zuni Conservation Project is now spearheading a program to revitalize agriculture on the reservation. Our research on Zuni agriculture is in support of this program.

Macrobotanical remains of maize cultivation have been radiocarbon-dated at about 2300 years old (date obtained by Steve Hall, geomorphologist in the Department of Geography, University of Texas at Austin) on the Zuni Reservation, thus demonstrating the antiquity of agriculture in the region. This finding indicates that Zuni fields are among the oldest, more or less continuously, cultivated lands in the United States. Evidence of early agriculture was recently found during an archaeological project (Damp and Kendrick 2000) in Y Unit Draw, which is on the west side of the Bear Canyon study unit along State Highway 602. Runoff irrigation canals and rock water control features dating to over 2000 B.P. (Basketmaker II period) were exposed in trenches and traced by remote sensing techniques, including archaeomagnetism and electrical resistivity.

Previous Soil Studies of American Indian Farming Systems

There have been few soil studies of American Indian farming systems, and most of those now available are based on very small sample sizes or are focused on ancient, abandoned systems lacking continuity to the present. Soil analysis of existing or recently abandoned American Indian farming systems was completed for Tohono O'otham (formerly known as the Papago) fields in southern Arizona, where runoff systems similar to those of Zuni were used. This work, completed as part of Gary Nabhans's dissertation, consisted of analysis of single soil samples from about 30 fields (Nabhan 1983).

Ancient agricultural soils of semiarid regions of the Southwest, including those of Zuni runoff fields, are well suited for agronomic research because soil-formation processes (e.g., weathering, leaching, and illuviation) proceed much more slowly in deserts than in humid environments, so soil changes caused by cultivation practices tend to persist and be detectable over the long-term. A few soil studies in the Southwest have found that ancient farming systems degraded the nutrient status of agricultural soils. For example, long-term cultivation significantly lowered the fertility of terraced fields in the Mimbres area (Sandor 1983, Sandor et al. 1986; Sandor et al. 1990), and farming practices at prehistoric fields near Flagstaff, Santa Fe, and at Mesa Verde tended to lower phosphate and other nutrients severely enough to cause fields to become unproductive and then abandoned (Arrhenius 1963). Other studies in central Arizona have found that soil fertility was probably not degraded by cultivation, and in fact, soil productivity was often enhanced (Homburg 1994, Homburg and Sandor 1997).

American Indian agricultural systems in the Southwest sharply contrast with those of the better-studied, modern agricultural systems of the American Midwest, where long-term soil degradation is virtually ubiquitous. Widespread assumptions of the consequences of agriculture, such as those derived from the Midwest (especially accelerated erosion, soil compaction, and nutrient depletion) are both untested and unwarranted in assessing American Indian agricultural systems of the Southwest, where fields are commonly placed to take advantage of natural erosional processes to offset nutrient losses to crop uptake. The few soil studies conducted thus far in the Southwest indicate that the consequences of traditional cultivation practices are highly variable in terms of soil productivity, due to many interacting environmental and cultural factors (e.g., climate, topography, hydrology, soil type, native vegetation, crop type and variety, agricultural technology, and duration and intensity of cultivation).

In Sandor's study of the long-term effects of cultivation in the Sapillo and Mimbres valleys of southwestern New Mexico, Mimbres agricultural terrace soils associated with small rock alignments were compared to uncultivated control samples (Sandor 1983, Sandor et al. 1986, Sandor et al. 1990). Field observations and lab data indicated that the primary anthropogenic soil changes were degradational, and that the effects of cultivation could still be detected about 800 years after the fields were abandoned. Sandor found that cultivated soils were lighter in color, more compacted, and had thicker A horizons with more blocky and less granular structural aggregates in comparison to uncultivated soils. He found that cultivated soils had lower organic carbon, nitrogen, total and available phosphorus, and copper levels, and higher manganese and pH values. Rock alignments primarily functioned as dams to reduce the velocity of runoff, increase infiltration, and thicken naturally thin A horizons by impounding sediments (Sandor et al. 1986). A controlled greenhouse experiment showed that chapalote, a primitive variety of maize, grown in terrace soils was stunted in the terrace soils due to nitrogen deficiency.

The findings of Sandor's Mimbres study contrasts strongly with that of two soil studies in Arizona, one in the Tonto Basin (Homburg 1994) and the other in the Horseshoe Basin (Homburg and Sandor 1997). Both studies were conducted in low desert settings of the Transition Zone northeast of Phoenix. The Horseshoe and Tonto basin studies focused on measuring the effects of cultivation on soil fertility by comparing rock mulched and terraced soils with uncultivated soils. This study found no evidence of soil compaction in cultivated soils, and nutrient levels were generally higher in agricultural contexts. Mulched soils generally had higher water infiltration rates and water retention levels than uncultivated controls.

There is no universally accepted method for assessing potential degradational effects of all agricultural soils. It is necessary to consider environmental and cultural factors such as climate, topography, hydrology, soil type, native vegetation, crop type and variety, agricultural technology, and duration and intensity of cultivation.

Rationale for Tests Used in this Soil Study

Major goals of our study are to document soil properties and assess anthropogenic effects of Zuni agriculture on soils in runoff fields. We aimed to determine the effects of long-term runoff agriculture on soil morphology, organic matter, and nutrients in the context of soil quality and sustainable land use (Arshad and Coen 1992, Papendick and Parr 1992). A common outcome of long-term agriculture is soil degradation, whereby changes in soil properties cause lower agricultural productivity. Many studies of modern and ancient agricultural soils have reported degradation in physical and chemical soil properties resulting from accelerated erosion, soil aggregate disruption by plowing or similar disturbance, use of heavy machinery, net nutrient removal by cropping, and salt accumulation (Lal and Stewart 1990). Common forms of degradation caused by agricultural land use include reduced nitrogen and phosphorus levels, depressed microbial activity and diversity, compaction, accelerated erosion, decreased A horizon thickness, and salinization.

Most quantitative documentation of agricultural soil degradation is in the context of modern conventional cultivation. Given major differences between modern agricultural systems and traditional runoff agriculture studied in environment, management practices, and time scale, unexpected or different forms of soil change may be encountered. Another important consideration regarding degradation concerns distinguishing short-term fluctuations in productivity versus more long-term soil degradative alterations. For example, decline in available nitrogen after several years of continuous cropping may be rectified by several years of fallow, but accelerated erosion may result in permanent degradation in terms of the human time scale.

Paired site sampling provides the basis for inferring soil changes resulting from agriculture. Difficulties in paired site studies and their statistical validity are recognized (Hurlbert 1984), but this widely used method can yield valuable information. Paired site comparisons are the only means now available for evaluating changes in ancient agricultural soils (Sandor and Eash 1991). Consequently, we used both paired (intensive) and unpaired (extensive) sampling methods to strengthen statistical comparisons of agricultural and uncultivated soils.

Each soil property measured is important for crop productivity, and soil changes were interpreted in this study by common criteria for assessing soil degradation. Soil properties being characterized are derived from the *minimum data set* and other properties commonly recognized as key indicators of soil quality (Arshad and Coen 1992, Larson and Pierce 1991, Larson and Pierce 1994). These include texture, organic matter, pH, nutrient status (N and P), bulk density, rooting depth, and soil hydrologic properties such as water-holding capacity and hydraulic conductivity. Given the paucity of previous research on Zuni agricultural soils, this minimum data set encompasses a range of basic soil characterization useful for evaluating soil quality.

Despite the large body of literature generated over the last decade that supports making soil quality assessments, we recognize that soil quality, how it is measured, and exactly what should constitute a minimum data set are not without ambiguity. There is no agreement on a single definition of soil quality, and even the validity of the soil quality concept has come under serious attack (Sojka and Upchurch 1999). As noted by Mausbach and Seybold (1998: 33), soil quality definitions range from simply *the capacity of a soil to function* (Pierce and Larson 1993) to more inclusive ones, including "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al. 1996). We agree with Kimble's (1998: 44) assertion that "There is no such thing as a minimum data set or a magic pill (data set) that we can or should collect to solve all problems." Despite criticisms of the soil quality concept, we still consider the soil properties examined by this study to be valid measures for evaluating soil degradation, even though the precise thresholds for pinpointing what constitutes soil degradation are debatable. This is especially true when trying to estimate thresholds for different agricultural systems, given the high degree of natural and cultural variability. It is necessary to consider the many environmental and cultural factors such as climate, topography, hydrology, soil type, native vegetation, crop type and variety, agricultural technology, and duration and intensity of cultivation. For the purpose of this study, criteria for evaluating possible degradation of agricultural soils relative to uncultivated soils are summarized in Table 3.1. Soil property changes listed under the heading, "criteria to recognize degradation", are widely used in soil quality assessments. Specific quantitative changes detected in soil properties will be interpreted in the context of the study area environment, because degradation thresholds vary with environmental sensitivity. For example, changes in available water capacity would probably impact crop productivity more significantly in the semiarid environment of the Zuni area than in humid regions where water is not a major limiting factor for plant growth.

Study Area

The study area is located in the southeastern Colorado Plateau, just west of the continental divide. Principal drainages in the eastern part of the reservation include Rio Nutria and Pescado, which join to form the Zuni River (see Figure 3.1), a tributary of the Little Colorado River. In the early 1900s several reservoirs were built along these drainages to obtain water for irrigation. These have since partially to completely filled with sediment, and thus destroyed vast areas of bottomland that were previously farmed.

The soil parent material consists chiefly of Quaternary alluvium weathered from Cretaceous sedimentary rocks, including sandstone, siltstone, mudstone, and shale. The predominant geologic units are the Gallup Sandstone and Crevasse Canyon formations (Anderson, et al. 1989, Orr 1987). Alluvial fans are within or flanking canyons cut into rocky mesas. Soil textures of these fans vary over short distances due to natural vertical and horizontal stratification processes and differences in geologic strata in the watersheds. In unpublished soil maps produced by Steve Parks of the National Resources Conservation

Table 3.1. Agricultural soil properties analyzed by this study.

Soil Property	Criteria for Recognizing Degradation: Typical Causes and Consequences
A horizon thickness	Decreased thickness caused by water or wind erosion. Reduces important organic matter-enriched surface layer that can be exploited by plants for water, nutrients, and oxygen. Shallower depth to possible root-limiting subsurface layers such as strongly developed argillic horizons.
Soil structure	Macromorphology: lowered grade of granular or subangular blocky structure, trend toward massive state, especially in surface horizons. Commonly results from compaction and organic matter decline. Micromorphological thin sections used compare structure and pore characteristics of cultivated and uncultivated A horizons.
Bulk density	Compaction (increase in bulk density above that of natural condition) associated with soil structure degradation. Compaction and structure degradation commonly retard seed germination and root growth, reduce root access to water, oxygen, and nutrients, reduce diffusion of gases, and decrease water infiltration and available water capacity.
Organic carbon	Decrease in organic C is common under conventional cultivation. Results from accelerated microbial oxidation of organic matter in disrupted, exposed soil aggregates, and other effects of agriculture. Numerous benefits of organic matter for soil physical, chemical, and biological properties important to plant growth are well documented.
Nitrogen	Decrease in total N accompanies declining organic matter in agricultural soils, though C:N ratio tends to decrease. Nitrate and ammonium are plant available forms of N, which is commonly a key limiting factor for plant growth in all regions, including arid regions.
Phosphorus	P (both total and available) is another macronutrient that has been shown to decrease under plow-based agriculture in some cases. P is a key ecological and soil indicator because of its low mobility, low availability to plants, and long-term stability of its forms in soils.
pH	Very high soil pH can indicate salt accumulation (which is measured by electrical conductivity). Sodic soil conditions (recognized by high exchangeable sodium) can be prevalent in agricultural soils of arid and semiarid regions. Detrimental effects on many plants, including crop species, occur both through direct chemical effects and through soil structural deterioration.

Service, Hosta soils are depicted on many alluvial fan settings in the study area. The tentative description of the Hosta series (National Cooperative Soil Survey website, revised in March, 1998) characterizes it as "very deep, well drained soils formed in fan alluvium and eolian deposits derived from sandstone and shale." Soils of the Hosta series are associated with 1 to 8 percent slopes, elevations of 6600 to 7500 feet (2012-2286 m), about 14 inches (356 mm) of annual precipitation, and the mean annual temperature is about 50 degrees F. The Hosta series is classified at the family level of Soil Taxonomy as Fine, mixed, superactive, mesic Aridic Haplustalfs. We concentrated our soil sampling on areas mapped as the Hosta series, but we often described pedons in the field that do not meet the criteria of the Hosta series.

Mixed mineralogy is reported for the Hosta and other soil series in our project area, based on soil series descriptions provided by the National Cooperative Soil Survey website. Supporting this assessment are limited data from x-ray diffraction (XRD) and differential thermal analysis (DTA) that we compiled. XRD and DTA analyses for Bt and C horizons and rock (mudstone) samples from the Laate watershed in the Lower Nutria area. We found that significant amounts of smectite and kaolinite are present in soils of the Upper Nutria area. Investigations by the New Mexico Bureau of Mines found that smectite and kaolinite are inherited from Cretaceous sedimentary rocks that surround the alluvial valleys (Orin Anderson 1996, NMBM geologist, personal communication). Minor volcanism during deposition of Cretaceous sediments formed beds of bentonite (the rock form of smectite) and kaolinite. Ash deposited in strongly acid environments of coal marshes was rapidly desilicified to form kaolinite, and ash deposited in drier environments formed bentonite. The fraction of smectite in soils resulting from neoformation is unknown. Regardless of the precise origin of clay minerals in the Zuni soils, mixed mineralogy is suggested.

The climate of our study area in the eastern part of the Zuni Reservation is temperate and semiarid, with annual precipitation averaging about 300 mm, which is about 50 mm less than is common for the Hosta series. The Zuni area has a summer-dominant rainfall pattern, and a frost-free season that typically extends from late May or early June to late October. During our second field season we even recorded a light freeze at the beginning of July. Snowmelt is an important source of soil moisture for crops after planting, and summer monsoons commonly supply moisture in the middle to late part of the growing season. Farming success often depends on receiving at least two or three storms to water the fields, and the timing of these events is critical for agricultural production. In many or even most years, farming of non-irrigated land in the Zuni area would not even be possible without supplemental water provided by runoff (Kintigh 1985). Rain during the growing season often consists of localized, torrential downpours in the afternoon and evening. Spatial and temporal variability in rainfall is extremely high in the Zuni area, so farmers commonly spread their fields across different soils and landforms as a coping mechanism. This technique was widely used in the Southwest to minimize the risk of crop failure.

Big sagebrush (*Artemesia tridentata*) and various grasses are common in uncultivated fields, and a variety of weedy grasses and forbs grow in abandoned fields. Uncultivated and fallow fields are mainly used as rangeland for cattle and sheep grazing. Rocky slopes and mesa tops overlooking alluvial fans and footslopes are commonly covered with juniper and pinyon (*Pinus edulis*) woodlands. Ponderosa pine (*P. ponderosa*) and Gambel's oak (*Quercus* *gambelii*) are common on cool, moist north slopes in the Pescado and Bear Canyon study areas. Nitrogen-fixing plants such as mountain mahogany (*Cercocarpus montanus*), deer vetch (*Lotus wrightii*), scurfpea (*Psoralea tenuflora*), and cryptogamic crusts are widespread in many upper watersheds, and these may play an important role in supplying nutrients to agricultural fields below.

FIELD AND LAB METHODS

Jon Sandor conducted the initial soil sampling at the Sanchez field in 1991, and Jay Norton and Jon Sandor completed work on this field during the summers of 1993 and 1994. Most fieldwork was completed between 1996 and 1998, as part of the NSF project. Fields were selected for soil sampling based on archival research. This work entailed: (1) inspecting General Land Office maps from the early 1900s that differentiate between cultivated, fallow, and uncultivated land; (2) examining aerial photographs from the 1930s to 1980s to differentiate fields that were consistently cultivated versus others; (3) reviewing archival data compiled by Martha Graham (1990) on individual fields; and (4) obtaining recommendations from farmers knowledgeable of the land-use history of different fields. In searching for paired fields we sought alluvial settings where we could clearly identify and distinguish between adjacent cultivated and uncultivated parcels for comparison. We sought cultivated fields that have been consistently used for agricultural production over the last century, fields that have been abandoned for several decades, and uncultivated fields of similar settings but lacking evidence of farming activity over the last century. It was more difficult to find suitable fields for the fields in the extensive sampling program, and in some cases, we worked on all or nearly all candidates that met our sampling criteria (that is, runoff fields with similar landforms, watersheds, elevations, and soil mapping units, and with well documented land-use histories). In some cases we had to reclassify fields before making statistical comparisons, based on new information on historic land use that was obtained after fieldwork was completed.

Three intensive cultivated and uncultivated field pairs were included in the sampling design, including the Sanchez field sampled prior to the start of this NSF project. Twenty-nine unpaired (extensive) fields were selected for soil analysis, divided between nine cultivated, ten abandoned, and ten uncultivated fields. At each paired and unpaired field, ten soil samples were collected from the upper 15 cm, which approximated the depth of the plow zone. An additional set of 10 samples was collected from the middle part of the Weekoty field. Sampling points were laid out in a five-by-two pattern in all fields, with a 10-m interval between sampling points. Soil samples were also collected by horizon from a soil pit placed in the middle of surface sampling points of each field. Observations on vegetation, percent surface cover, and organic debris (e.g., plant and fecal matter) were noted for soil-sampling points, because of potential effects they could have on soil-test results. Four auger holes were placed at the corner soil-sampling points. Auger holes provided data on horizonation, textural trends with depth, and lateral variability in soils.

A 1 by 2 m or 1 by 1 m soil pit was excavated at all fields to a depth of about 0.75 to 1.5 m, and the soil profile was described, sampled, and photographed. General photographs of alluvial fans, fields, soil sampling locations, and other noteworthy observations were taken. Sketch maps were drawn to depict soil-sampling points in relation to topography and noteworthy features (e.g., rock outcrops, roads, archaeological sites, etc.). Morphological properties (e.g., depth, color, texture, structure, consistence, etc.) were described and soil horizons were designated in accordance with procedures of the soil survey manual (Soil Survey Staff 1993). Pedons were classified using the most recent taxonomic references (Soil Survey Staff 1998, Soil Survey Staff 1999). The bottom of each pit was augered to obtain information on soils and sediments below the bottom of our soil pits.

To document A horizon thickening caused by runoff sediment management , depth to illuvial clay was documented throughout the alluvial fans of two intensive fields, the Sanchez and Weekoty fields. The alluvial fan at and above the Sanchez field was augered or shovel-probed at 40-m intervals along a 1-km-long transect running the length of the fan, and at perpendicular transects spaced every 80 m. For the alluvial fan of the Weekoty field, sampling was conducted using shovel probes in a grid pattern with a 40-m interval between the grid points. There were 56 sampling points in the Sanchez field and 48 in the Weekoty field.

Maps of the illuvial clay distributions were produced with a mapping program (Surfer, version 6.0) using a kriging algorithm to project spatial trends within and adjacent to our sampling points. Kriging, as originally defined, is a geostatistical method that has come to be equated with "spatial optimal linear prediction" (Cressie 1990). We used Surfer's default linear variogram, which produces a reasonable depiction of the spatial distribution if the nugget effect is not used (Golden Software, Inc. 1999). Surfer's default setting does not use a nugget effect, and there is strong support for this approach. Cressie (1991) questions including Matheron's (1962) nugget effect in a mathematical model, because it assumes that microscale variation (or small nuggets) is discontinuous. Cressie notes that the validity of this assumption is unproven.

Twelve samples were collected for soil micromorphological analysis. Micromorphology samples were collected from pedestals of the upper 10 cm, including two cultivated and two uncultivated samples from each of the three intensive fields. Samples were collected in the same area where bulk 0-15 cm samples had been collected for soil analyses. The micromorphology samples were carefully wrapped, cushioned, and transported in an attempt to maintain their structural integrity. They were then shipped to Spectrum Petrographics, Inc. in Winston, Oregon for processing. Processing tasks included impregnating samples with epoxy, cutting 30-micrometer thin sections with a rock saw, and then polishing and mounting the thin sections on slides. Thin sections were examined at various scales using a Nikon petrographic microscope. Analysis focused on quantifying structural aggregate and pore types by point-counting along every fifth transect at 20x, at a step interval of 300 micrometers. Slides were also scanned at scales ranging from 10x to 100x to document selected pedo- and biological features (e.g., clay and organic matter coatings, iron oxides, fecal matter, plant residues), and search for differences between cultivated and uncultivated soils, using terms recommended in the International Soil Science Society (1985) "Handbook for Soil Thin Section Description. Structural aggregate and pore types were quantified by point-counting along every fifth transect at 20x, at a step interval of 300 micrometers. Photographs were taken of noteworthy features in plane- and cross-polarized light.

Chemical analyses included determinations of pH, organic carbon, nitrogen, and total and available phosphorus. Particle-size, bulk density, and pH analyses were completed at Iowa State University. Organic carbon, total nitrogen, and total and available phosphorus analyses were conducted at the University of Montana under the supervision of Jay Norton. Subsamples for each laboratory test were taken from bulk samples collected in the field. Initial sample preparation involved air-drying and sifting samples through a 2-mm sieve to remove gravel, roots, and other coarse undecomposed organic debris. Organic carbon, nitrogen, and total phosphorus analyses were done on 10-g subsamples mechanically ground to pass through a No. 100 sieve.

Particle-size distributions were determined using the sieve and pipette method (Gee and Bauder 1986: Method 5.4), with samples pretreated with a 30 percent hydrogen peroxide reagent for organic matter digestion and a sodium hexametaphosphate solution for clay dispersion. Bulk density analysis was measured using the clod method, with paraffin-coated peds (Blake and Hartge 1986: Method 13.4). Bulk density samples were analyzed in duplicate and averaged; for samples with a coefficient of variation exceeding 5%, a third sample was analyzed and averaged with the other two. After weighing peds in water, paraffin coatings were removed, and the gravel was removed and weighed, thereby enabling bulk density determinations of the <2 mm fraction alone. Soil pH was measured electrometrically in the lab using a 1:1 suspension (weight basis) of soil and distilled water using a glass electrode (McLean 1982). In addition, pH was estimated by colorimetry in the field and these results are included in the pedon descriptions (Appendix A). Total carbon and nitrogen concentrations were determined using a Leco CHN analyzer. Total carbon content was assumed to be identical or very similar to organic carbon levels because of the near to total absence of carbonates in the samples. Inorganic carbon was determined for some samples, especially those that effervesced when treated with dilute hydrochloric acid. Total phosphorus concentrations were determined using an alkaline oxidation extract (Dick and Tabatabai 1977), and available phosphorus was measured using the Olsen extraction method (Olsen 1982: Method 24-5.5.20; extract of 0.5 M $NaHCO_3$ at pH 8).

We used one-way analysis of variance (ANOVA) to test for statistically significant differences between the physical and chemical soil test values of cultivated and uncultivated soil samples for each pair of intensive fields. Paired *t*-tests were used to test for overall differences between cultivated and uncultivated field. One-way ANOVA was used to test for differences between extensive fields, using a randomized block design with treatments consisting of the types of soil management (cultivated, abandoned, and uncultivated) and blocks consisting of the three study areas (Bear Canyon, Nutria, and Pescado). In contrast to the intensive study, where the experimental unit of analysis was the individual soil samples, the unit of analysis for the extensive study was the mean of ten samples from each field. Exploratory data analysis was also used to search for patterning in the extensive soil data. Scatter plots of all soil tests were examined to visually search for potential linear or random relationships between variables and to search for potential outliers that could significantly skew the ANOVA tests. We used correlation matrices to quantify the relationship between soil test variables. Levels of significance were defined at the 0.05 and 0.01 levels for all statistical tests but the paired t-tests. The latter were evaluated at a level of 0.2 because of the small sample size, based on consultation with and recommendations by a statistician, Phil Dixon.

ANOVA and paired t-tests for the intensive fields, and correlation analyses for both intensive and extensive data sets were completed using Quattro-Pro, Version 7.0. Soil data for extensive fields were analyzed using the General Linear Model of SAS. Multivariate analysis of variance (MANOVA) was conducted using SAS to test for overall differences due to treatment effects for the extensive data set. MANOVA tests were calculated using four types of F statistics, including Wilks' lambda, Pillai's trace, Hotelling-Lawley trace, and Roy's greatest root. In addition to blocking on the three study areas, posteriori blocking of other potential sources of variability was done for the extensive fields. Posteriori blocks consisted of landforms, landscape positions (within versus outside of canyons), and groupings of the amount of clay and sand. Posteriori tests were made using SAS's calculations of Type III sum of squares, which are the partial (also referred to as uniquely attributable or fully adjusted) sum of squares.

RESULTS AND DISCUSSION

Soil Classification and Morphology

Soils in the three intensive fields of our study were classified in three different soil orders (Table 3.2; see Appendix A for pedon descriptions). The pedons documented in the Laate field in the Nutria study area are Entisols with a high clay content and a possible buried argillic horizon. Recent sedimentation accounts for the lack of surface pedogenic development in the Laate field. The pedons of the Sanchez field in the Pescado study area are Alfisols marked by minimally developed argillic horizons; and pedons described in the Weekoty field in the Bear Canyon study area are Mollisols. Epipedons of Mollisols of the

Table 3.2. Taxonomic soil classification and landform of intensive and extensive fields.

Fields	Soil Order	Soil Family	Landform
Intensive Fields			
Laate, Cult	Entisol	Fine-loamy, mixed, mesic Aridic Ustifluvent	Distal fan/alluvial plain
Laate, Uncult	Entisol	Fine-loamy, mixed, mesic Aridic Ustifluvent	Distal fan/alluvial plain
Sanchez, Cult	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalf	Middle fan
Sanchez, Uncult	Alfisol	Fine, mixed, mesic Aridic Haplustalf	Middle fan
Weekoty, Cult	Mollisol	Fine-loamy, mixed, mesic, Aridic Argiustoll	Middle fan
Weekoty, Uncult	Mollisol	Fine-loamy, mixed, mesic, Aridic Argiustoll	Middle fan
Extensive Fields			
Cultivated			
NC1	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Colluvial footslope
NC2	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Lower fan
NC3	Mollisol	Fine-loamy, mixed, mesic Aridic Argiustolls	Colluvial footslope
PC1	Entisol	Nonacid, mixed, mesic Aridic Ustifluvents	Middle fan
PC2	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Lower fan
PC3	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Colluvial footslope
BC1	Inceptisol	Coarse-loamy, mixed, mesic Aridic Haplustepts	Upper fan
BC4	Inceptisol	Fine-loamy, mixed, mesic, Aridic Haplustepts	Middle fan
BC5	Inceptisol	Coarse-loamy, mixed, mesic Aridic Haplustepts	Lower fan
Abandoned			
NA1	Alfisol	Fine, mixed, mesic, Aridic Haplustalfs	Middle fan
NA2	Alfisol	Fine, mixed, mesic, Aridic Haplustalfs	Colluvial footslope
NA3	Inceptisol	Fine-loamy, mixed, mesic Fluventic Haplustepts	Middle fan
PA1	Alfisol	Fine-loamy, mixed, mesic, Aridic Haplustalfs	Middle fan
PA2	Inceptisol	Coarse-loamy, mixed, mesic Fluventic Haplustepts	Lower fan
PA3	Inceptisol	Fine-loamy, mixed, mesic Aridic Haplustepts	Lower fan
BA1	Inceptisol	Fine, mixed, mesic, Fluventic Haplustepts	Middle fan
BA2	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Middle fan
BA3	Alfisol	Fine-loamy, mixed, mesic, Aridic Haplustalfs	Middle fan
BA4	Alfisol	Fine-loamy, mixed, mesic, Aridic Haplustalfs	Middle fan
Uncultivated			
NU1	Alfisol	Fine, mixed, mesic, Aridic Haplustalfs	Lower fan
NU2	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Middle fan
NU3	Entisol	Coarse-loamy, mixed, calcareous, mesic Aridic Ustifluvents	Middle fan
PU1	Alfisol	Fine, mixed, mesic, Aridic Paleustalfs	Middle fan
PU2	Alfisol	Fine-loamy, mixed, mesic Aridic Haplustalfs	Middle fan
PU3	Alfisol	Fine, mixed, mesic, Aridic Paleustalfs	Middle fan
BU1	Inceptisol	Fine-loamy, mixed, mesic Fluventic Haplustepts	Middle fan
BU2	Alfisol	Coarse-loamy, mixed, mesic Aridic Haplustalfs	Middle fan
BU3	Alfisol	Coarse-loamy, mixed, mesic Aridic Haplustalfs	Middle fan
BU4	Alfisol	Fine, mixed, mesic, Aridic Haplustalfs	Middle fan

B - Bear Canyon, N - Nutria, P - Pescado, C - cultivated, A - abandoned, U - uncultivated

Weekoty field only marginally met the mollic color requirement, and we found that Alfisols dominate most of the alluvial fan outside of our soil sampling area. In contrast to the mid-fan position of the Sanchez and Weekoty fields, the Laate field is situated on a distal fan/alluvial plain. The Sanchez and Weekoty soils are more representative of the type of soils found in most of the extensive fields examined by our study.

Subgroup designations for soils in the extensive fields are compared to those intensive fields in Table 3.3. The 29 extensive fields include 18 Alfisols (62%), eight Inceptisols (28%), two Entisols, and one Mollisol (see Table 3.2). It is noteworthy that most Inceptisols (63%) have Bt horizons. Clay films were found on ped faces, but they lack sufficient illuvial clay accumulations to qualify as Alfisols (see soil data in Appendix B). For the purposes of agricultural production, Inceptisols (Aridic Haplustepts) are very similar in soil development and texture to many of the Alfisols (Aridic Haplustalfs). The presence of Bt horizons, with or without sufficient clay to classify as argillic horizons, is probably a critical factor in successful runoff farming at Zuni and elsewhere throughout much of the Southwest. Argillic horizons hold moisture in the rooting zone for considerable periods after rainfall events and snowmelt. We found that plant available moisture of argillic horizons in the Sanchez and Weekoty fields averages 57% higher than that of overlying topsoils on a relative basis, and 7% higher on an absolute basis. Further support for the effectiveness of argillic horizons for holding moisture was provided by field observations while excavating our soil pits; we commonly found much higher moisture levels in the shallow Bt horizons than overlying horizons, weeks to months after any significant precipitation. It is noteworthy that we often observed Zuni farmers digging shovel pits to check moisture levels in the upper soil

Table 3.3. Summary of soil subgroup of intensive and extensive fields.

Soil Subgroup	Intensive Fields		Extensive Fields			Total
	Cultivated	Uncultivated	Cultivated	Abandoned	Uncultivated	
Aridic Haplustalfs	Sanchez	Sanchez	NC1-2, PC2-3	BA2-4, NA1-2, PA1	BU2-4, NU1-2, PU2	18
Aridic Paleustalfs					PU1, PU3	2
Aridic Haplustepts			BC1, BC4-5	PA3		4
Fluventic Haplustepts				BA1, NA3, PA2	BU1	4
Aridic Argiustolls	Weekoty	Weekoty	NC3			3
Aridic Ustifluvents	Laate	Laate	PC1		NU3	4
Total	3	3	9	10	10	35

B - Bear Canyon, N - Nutria, P - Pescado, C - cultivated, A - abandoned, U – uncultivated

horizons as a quick way to determine when to plant their crops to ensure germination and seedling emergence.

Soils in over half the fields have soils that are in fine-loamy families, and the rest are about evenly divided between fine and coarse-loamy families. Soil textures are dominated by sandy loams and loams, followed in abundance by clay loams, silty clay loams, sandy clay loams, and rarely, clays and silty clays. The loamy soils so prevalent in the eastern part of the Zuni Reservation are generally well suited for cropping because of their ability to hold moisture and nutrients that are readily accessible to plant roots. No obvious differences in soil color were noted between cultivated, abandoned, and uncultivated soils. This finding suggests there is little difference in organic matter content.

Soil micromorphology supports the assessments of soil structure made at a hand-specimen scale in the field. Figure 3.6a depicts the better granular development of the uncultivated Sanchez soil compared to its cultivated counterpart, where disruption caused by

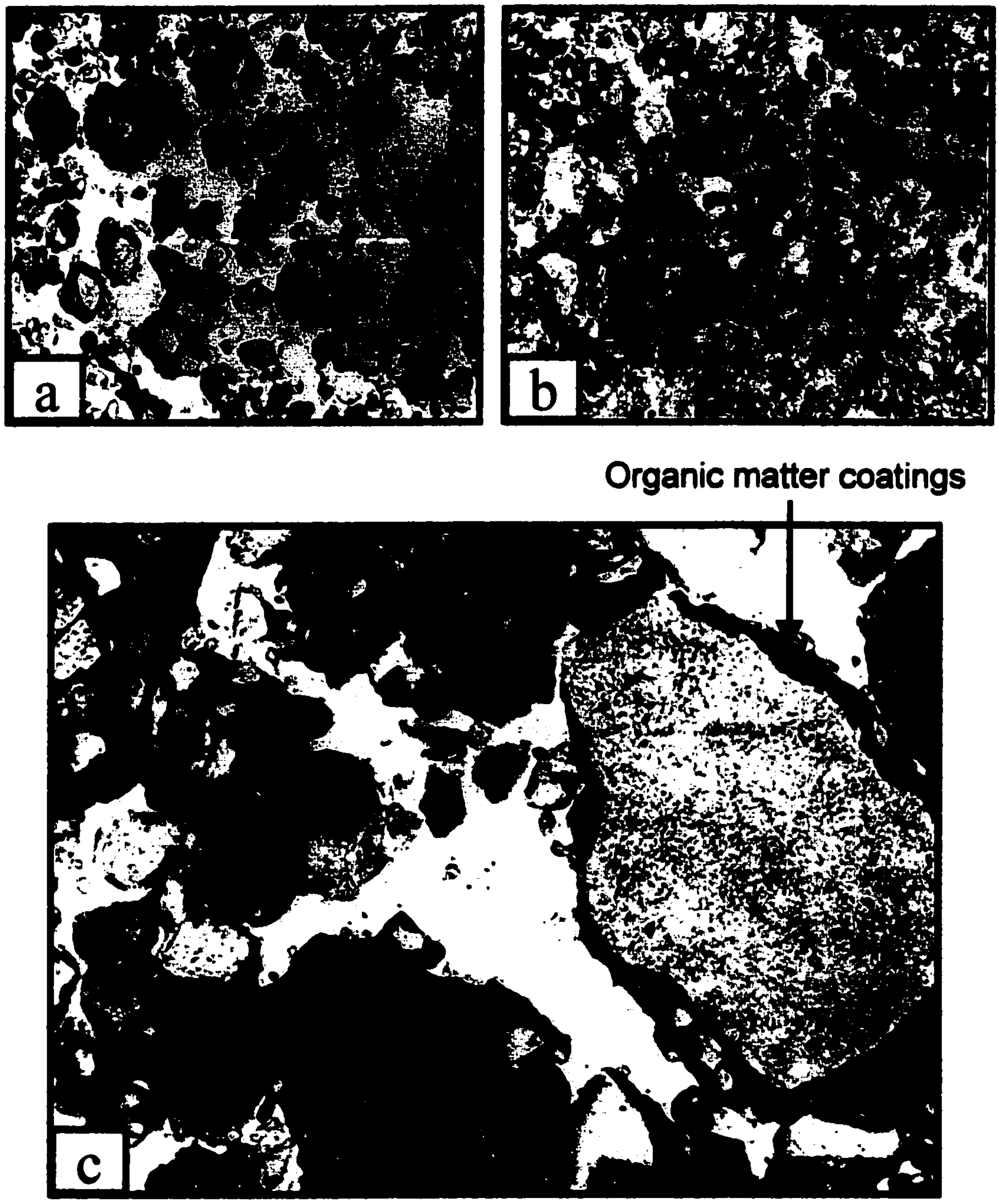


Figure 3.6. Photomicrographs of soils from the Sanchez field: (a) granular structure of uncultivated soil; (b) massive structure of cultivated soil; (c); organic matter coatings on grains and peds (All samples from 0-10 cm depth; scale: frame length = 7 mm for all photos).

plowing has resulted in more massive structure (Figure 3.6b). The differences between Figures 3.6a and 3.6b are dramatic for illustrative purposes. Granules actually do exist in the cultivated soils, but with less frequency. The trend toward more massive microstructure in cultivated soils, however, was repeated in comparisons of all fields (Figure 3.7). Each stacked bar in Figure 3.7 represents a mean of two samples analyzed by point-counting. Soil micromorphology helps quantify an important trend in anthropogenic influences on soil structure. Based on these data, we would expect that aeration and hydraulic conductivity would be reduced in the cultivated soils. Because a step interval of 300 micrometers was used in the point-counting procedure, microstructure and pores smaller than this size are not effectively characterized by this analysis.

One important finding of the profile descriptions is that A horizons tend to be thicker and Bt horizons deeper in the cultivated soils (Figure 3.8). This is the opposite of the pattern in most agricultural systems today, especially heavily mechanized systems that are often subject to accelerated wind and sheet wash erosion relative to natural (or uncultivated) settings. Previous studies of ancient American Indian agricultural fields in the Southwest indicate that bulk density of cultivated may be increased (Sandor 1983, Sandor et al. 1986) or not (Homburg 1994, Homburg and Sandor 1997). Topsoil thickening in the Zuni cultivated fields is explained by two factors. One is simply that plowing has disturbed the soil by ripping up and incorporating the upper BAt horizon into the overlying A horizon, thus producing a thickened Ap horizon. But this process is insufficient for entirely explaining all A horizon thickening, because the thickness commonly exceeds the approximate 15-cm depth of plowing. So sedimentation must play an important role in the thickening process as well.

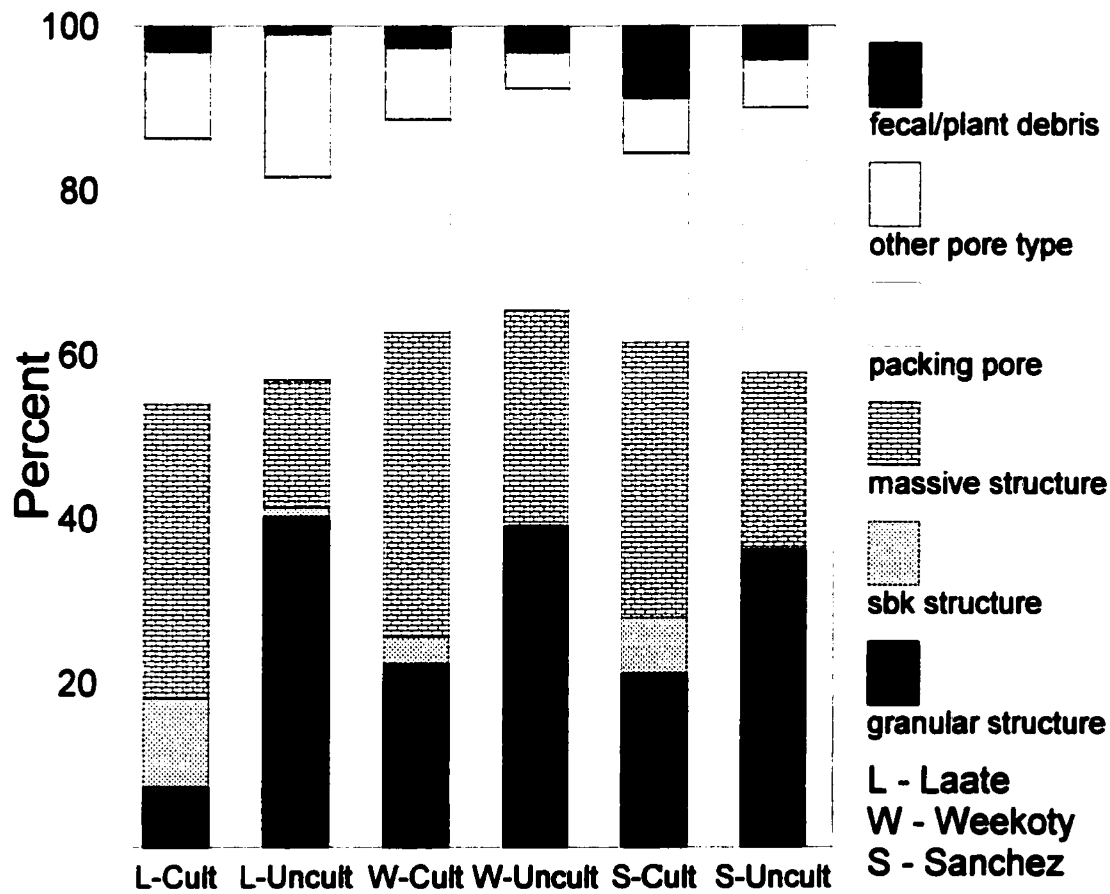


Figure 3.7. Comparison of solid and pore volumes, and structural aggregate and pore types in soils of intensive fields.

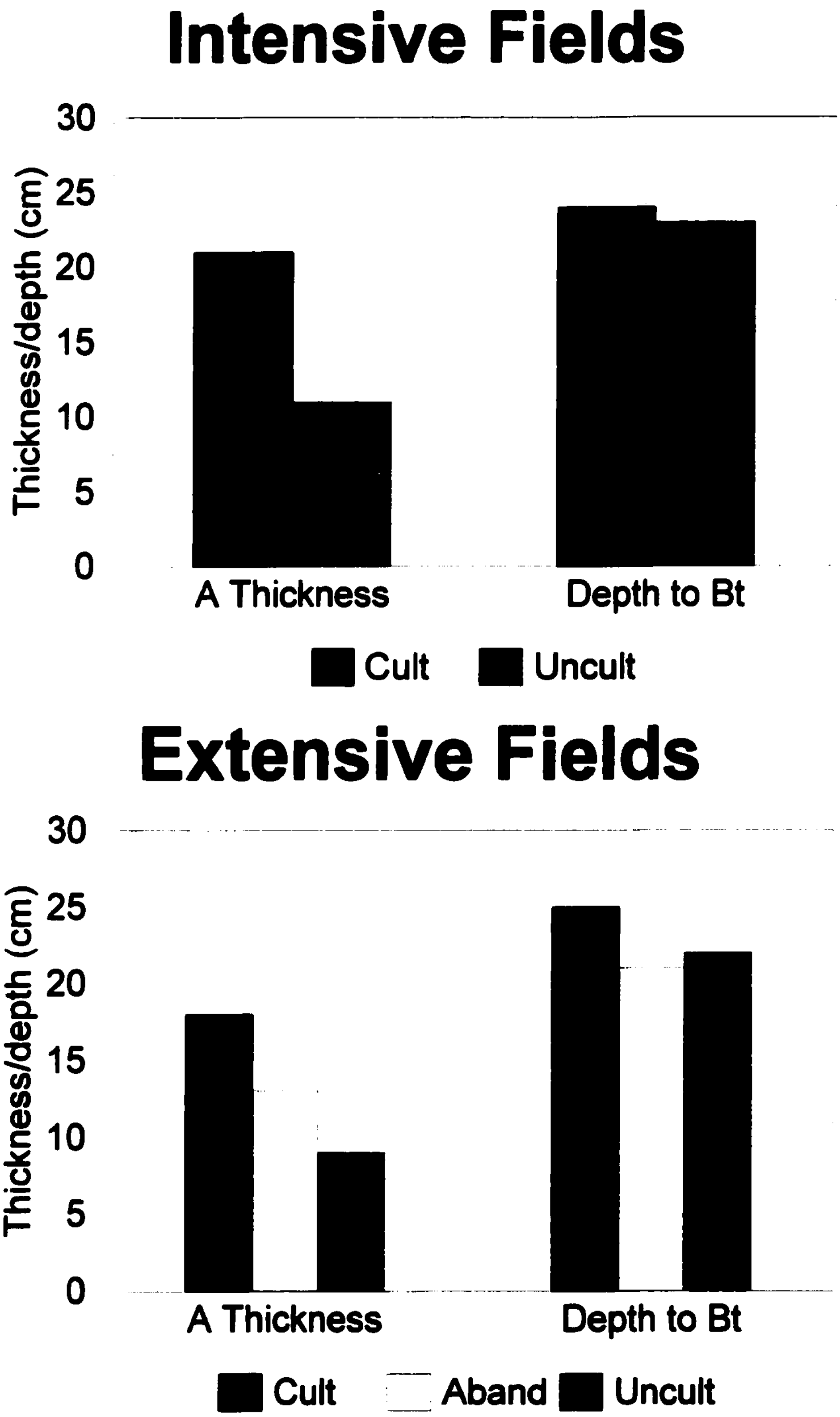


Figure 3.8. A horizon thickness and depth to Bt horizon in intensive and extensive fields.

Supporting this interpretation is our finding of laminated zones within the plow zone, which clearly shows that sedimentation is contemporaneous with the timing of farming in these fields (Figure 3.9). Interestingly, similar laminated zones were also observed in buried agricultural contexts that are about 2000 years old (Damp and Kendrick 2000), thus showing long-term continuity in this important nutrient renewal process. Nutrient-rich organic debris is commonly carried from the upper watershed by runoff water and incorporated in laminated alluvium. Undoubtedly, we would have found even more laminated strata within plow zones of fields today if plowing did not mix the soil on a regular basis. Evidence of laminated sediments is only preserved when the fields are left unplowed after a depositional event. Observations of rainfall and sedimentation events during the course of our fieldwork suggest that sedimentation is not a significant process on a yearly basis in runoff fields. Instead, storm events sufficient for generating runoff with enough energy to transport organic-rich sediment from the watershed are more infrequent, perhaps in the range of decadal intervals.

Spatial distributions in the depth to illuvial clay are shown in Figure 3.10. The terrain slopes northward in the Sanchez field and to the east in the Weekoty field. Both fields are situated within or in close proximity to places on alluvial fans where the depth to BAt and Bt horizons is greater. The implications of this finding for agriculture use, however, are unclear. Both the Weekoty and Sanchez fields are located in middle fan settings, but illuvial clay is much deeper in the upper Sanchez field (the southern part of the field where our intensive soil-sampling transects were placed). There is actually lower clay content in the buried Bt of the cultivated soil relative to the overlying A, Bw, and Bk horizons, so the upper part of this

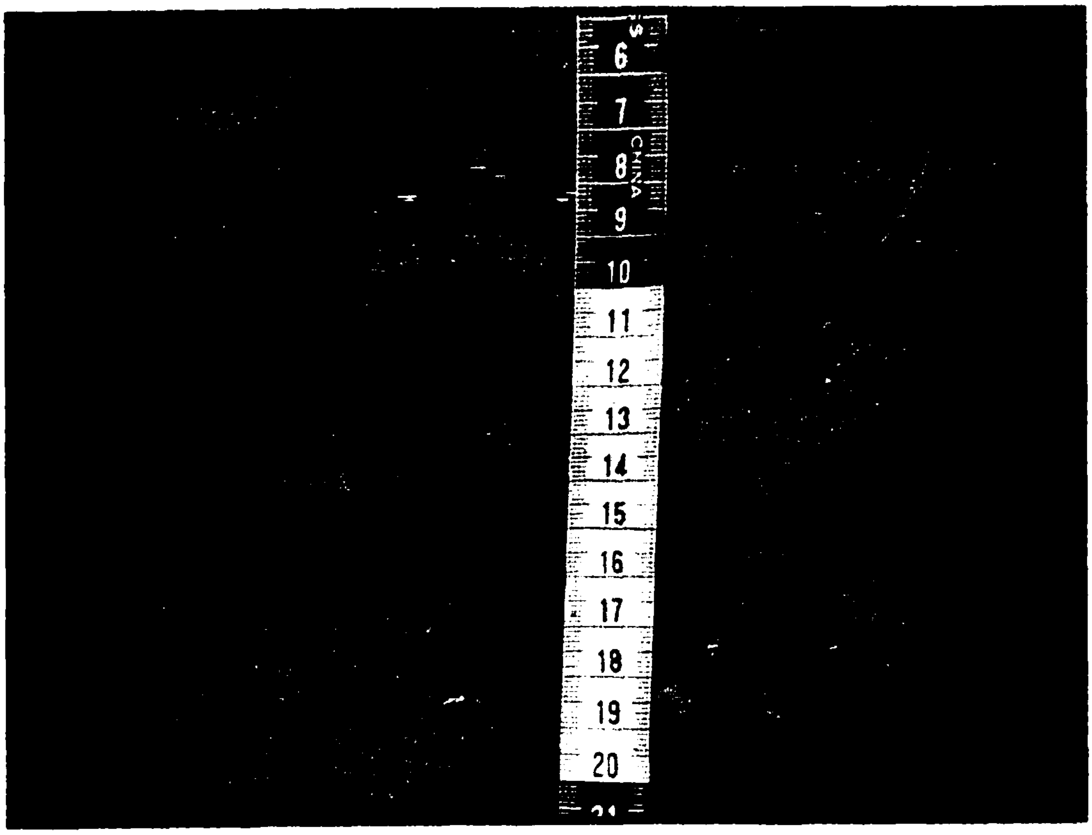


Figure 3.9. Ap/C horizon of abandoned field. (Note laminations within plow zone, which indicate sedimentation after plowing.)

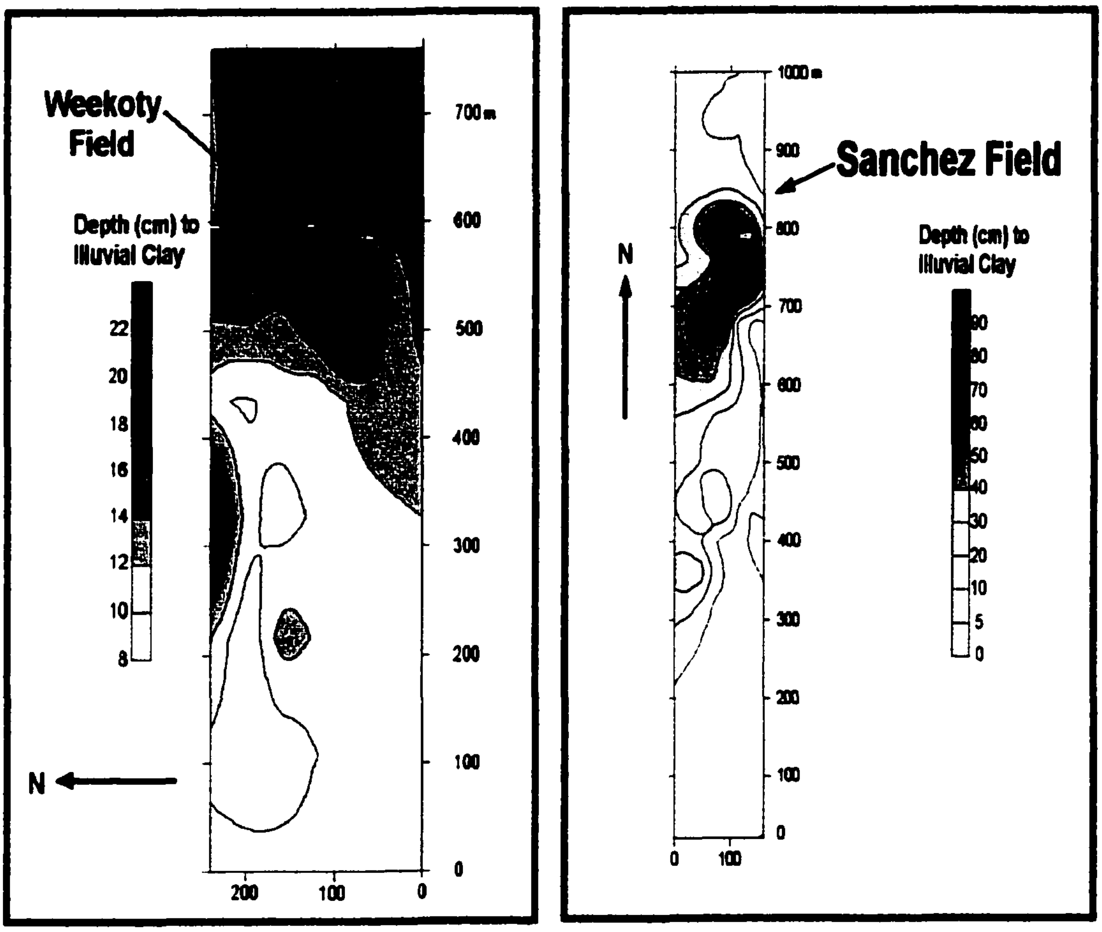


Figure 3.10. Depth to illuvial clay in Weekoty and Sanchez fields.

soil actually has a higher water-holding capacity than below. The higher clay content of the upper Sanchez soil is due to sedimentation on the fan, not soil formation. The greater depth to illuvial clay in the upper Sanchez field may be the result of increased sedimentation caused by human manipulation of runoff for agricultural use. Alternatively, the deep illuvial zones may be the result of natural sedimentation that pre-dates agricultural activity. Radiocarbon dates or diagnostic artifacts (especially decorated pottery) are needed before we can assess the time represented by deposition above the Bt horizon.

The Weekoty field straddles the edge of an area with the deepest illuvial clay. Illuvial clay accumulation zones in this field are both: (1) shallow enough for the upper rooting zone to take full advantage of greater water-holding capacity in and just above the argillic horizon; and (2) deep enough to provide a thicker rooting zone above it than in other parts of the fan. Further work is needed to explain the relationship between illuvial clay distributions and Zuni runoff fields, but the Weekoty field appears more typical of other runoff fields given the relative shallowness of BAt and Bt horizons of most extensive fields in our study. Buried Bt horizons were often found in extensive fields, but they usually underlie zones with lower clay contents. The overlying A horizons above respective buried Bt horizons are commonly absent due to sheet erosion.

Physical and Chemical Soil Properties

A total of 595 bulk soil samples were collected and analyzed for the Zuni agricultural soil study. This constitutes the largest data set analyzed from an American Indian agricultural system to date. In all, 360 samples were collected from the 0-15 cm sampling points (70 from the intensive and 290 from extensive fields) and 235 samples were collected from soil profiles and augers (55 from intensive and 180 from the extensive fields). Data for the individual samples and means for intensive fields are shown in Table 3.4, and means for the extensive fields are presented in Table 3.5. Means are shown graphically for the chemical and physical tests in Figures 3.11-3.14.

Overall differences between intensive cultivated and uncultivated fields are shown by *t*–tests in Table 3.6. Increased pH was found in many comparisons of uncultivated and agricultural contexts, due to incorporation of debris high in bases from the watershed. We found patchy concentrations of carbonate in soils under juniper canopies of upper watersheds, where much of the *tree soil* that naturally fertilizes agricultural fields below is derived. By contrast to runoff systems, reduced pH levels are nearly ubiquitous in agricultural systems, especially those dependent on artificial NH_4-N fertilizers that produce H^+ during nitrification (Tisdale et al. 1993. Increased pH is highly to very highly significant for the Weekoty and Sanchez fields (Table 3.7). The lack of statistical differences in pH for the Laate field is likely a function of buffering effects of the higher pH levels in these soils. The Laate soils are calcareous, with pHs in the slightly alkaline range (ca. pH 7.7), which is not high enough to cause serious deficiencies in nutrient availability for maize or cause dispersion of soil aggregates. No statistical differences in pH were noted for the extensive fields, but the same general trends were found (Table 3.8). Cultivated fields average pH 7.0, which is higher than the pH 6.9 and 6.7 of the abandoned and uncultivated fields, respectively.

Trends in organic C, one of the most useful measures of soil fertility and the effects of cultivation (Fenton et al. 1999), varied between treatments. No statistical difference was

Table 3.4. Soil data for intensive fields.

Field	pH	Org C	N	C:N	Av P	Total P	Bulk Den.	Sand	Silt	Clay
		(g/kg)			(mg/kg)		(g/cm3)		(%)	
Laate, Cult.										
C-1	7.7	9.5	0.71	13.4	12.3	420	1.55	43	32	26
C-2	7.7	12.3	0.85	14.5	11.5	466	1.53	36	39	25
C-3	7.8	10.9	0.76	14.4	10.7	465	1.54	37	39	24
C-4	7.8	10.4	0.76	13.6	11.5	455	1.48	37	37	25
C-5	7.7	11.4	0.76	15.0	11.7	427	1.54	34	40	25
C-6	7.7	9.8	0.76	12.8	11.7	456	1.59	41	36	23
C-7	7.7	8.1	0.67	12.1	10.5	401	1.54	49	29	22
C-8	7.8	9.3	0.69	13.4	10.2	396	1.55	46	31	23
C-9	7.8	10.2	0.74	13.8	8.5	405	1.46	42	35	23
C-10	7.8	8.0	0.65	12.3	10.1	381	1.58	51	29	20
Mean	**7.8**	**10.0**	**0.74**	**13.5**	**10.9**	**427**	**1.54**	**42**	**35**	**24**
Laate, Uncult.										
U-1	7.8	7.9	0.63	12.6	8.8	430	1.46	50	27	23
U-2	7.2	17.5	1.26	13.9	20.2	524	1.40	36	38	26
U-3	7.6	6.6	0.60	11.1	10.7	393	1.46	54	27	19
U-4	7.8	13.0	0.82	15.9	11.0	441	1.45	49	26	25
U-5	7.8	18.3	1.10	16.6	9.3	470	1.34	30	43	27
U-6	7.7	9.3	0.72	12.9	11.5	460	1.46	45	28	27
U-7	7.7	7.5	0.63	11.8	9.5	415	1.43	40	34	25
U-8	7.7	13.3	0.92	14.5	13.6	479	1.50	45	32	23
U-9	7.9	15.3	0.88	17.4	9.9	460	1.28	31	41	28
U-10	7.6	16.7	1.07	15.6	13.5	505	1.40	24	48	29
Mean	**7.7**	**12.5**	**0.86**	**14.2**	**11.8**	**458**	**1.42**	**40**	**35**	**25**
Weekoty, Cult.										
C-1	6.6	11.3	0.94	12.0	7.8	254	1.52	70	18	12
C-2	7.0	9.5	0.82	11.6	11.1	273	1.57	64	24	12
C-3	7.0	8.6	0.75	11.5	5.5	253	1.51	65	21	14
C-4	6.8	7.5	0.66	11.3	6.4	248	1.48	68	19	13
C-5	6.6	10.4	0.93	11.2	1.9	261	1.62	67	20	14
C-6	6.4	9.7	0.78	12.4	7.6	271	1.53	66	19	15
C-7	7.5	7.0	0.59	11.9	5.1	237	1.42	66	23	11
C-8	7.0	6.9	0.62	11.2	5.7	232	1.52	68	17	15
C-9	6.9	7.4	0.64	11.5	5.1	250	1.55	66	18	16
C-10	6.7	6.3	0.55	11.4	3.5	217	1.52	66	18	16
Mean	**6.8**	**8.5**	**0.73**	**11.6**	**6.0**	**250**	**1.52**	**66**	**20**	**14**
Weekoty, Uncult.										
U-1	6.3	13.5	1.02	13.3	5.6	276	1.40	52	34	15
U-2	6.4	13.6	1.03	13.2	9.0	319	1.49	50	36	14
U-3	6.8	14.0	1.05	13.3	6.8	290	1.52	52	29	19
U-4	6.0	13.4	1.08	12.4	6.1	263	1.40	63	24	13
U-5	6.2	9.8	0.81	12.1	4.6	238	1.54	68	20	12
U-6	6.3	14.8	1.12	13.2	7.0	284	1.52	54	33	12
U-7	6.3	32.7	2.23	14.6	13.8	411	1.39	31	45	24
U-8	6.9	16.7	1.35	12.4	16.2	375	1.44	52	30	18
U-9	6.4	11.3	0.91	12.3	4.4	276	1.42	60	25	16
U-10	6.4	8.5	0.74	11.5	5.7	272	1.36	67	19	14
Mean	**6.4**	**14.8**	**1.13**	**12.8**	**7.9**	**300**	**1.45**	**55**	**30**	**16**

Table 3.4. (continued).

Wekooty, Cult. (mid-field)										
C2-1	6.9	7.2	0.59	12.3	--	--	1.49	67	19	14
C2-2	6.9	12.6	1.02	12.4	--	--	1.48	67	20	13
C2-3	7.0	15.0	1.24	12.1	--	--	1.57	67	22	11
C2-4	7.4	10.9	0.82	13.4	--	--	1.49	67	21	12
C2-5	7.5	9.9	0.79	12.5	--	--	1.47	70	20	10
C2-6	7.0	6.7	0.59	11.4	--	--	1.53	66	23	11
C2-7	7.4	8.3	0.64	12.9	--	--	1.62	70	20	10
C2-8	7.4	7.9	0.65	12.1	--	--	1.53	63	23	14
C2-9	7.5	11.7	0.85	13.8	--	--	1.53	62	24	14
C2-10	6.8	5.7	0.47	12.3	--	--	1.56	73	16	10
Mean	**7.2**	**9.6**	**0.77**	**12.5**	--	--	**1.53**	**67**	**21**	**12**
Sanchez, Cult.										
C-1	6.9	23.2	1.61	14.4	10.2	267	1.61	24	46	30
C-2	6.8	24.7	1.68	14.6	12.6	340	1.55	23	47	30
C-3	7.4	24.5	1.05	11.5	7.2	243	1.60	24	42	34
C-4	7.5	10.1	0.91	11.1	5.8	321	1.74	31	38	31
C-5	7.4	9.5	0.80	11.9	6.3	306	1.63	42	31	27
C-6	7.1	13.5	0.83	16.2	6.9	297	1.63	38	36	26
C-7	6.9	22.4	1.54	14.5	12.1	370	1.59	36	38	26
C-8	6.9	18.8	1.42	13.3	9.5	207	1.58	29	42	29
C-9	7.1	10.6	0.96	11.1	6.2	248	1.66	29	40	31
C-10	7.1	9.1	0.80	11.4	5.6	356	1.75	38	35	27
Mean	**7.1**	**16.6**	**1.16**	**13.0**	**8.2**	**296**	**1.63**	**31**	**40**	**29**
Sanchez, Uncult.										
U-1	7.0	13.6	0.95	14.3	8.0	212	1.43	55	28	17
U-2	7.0	6.2	0.45	13.7	5.7	237	1.56	69	21	10
U-3	6.8	17.2	1.03	16.7	6.5	218	1.46	44	40	16
U-4	6.4	26.8	1.92	14.0	11.3	243	1.26	33	48	19
U-5	6.9	8.1	0.67	12.1	5.6	174	1.55	50	31	19
U-6	6.9	7.9	0.57	13.9	9.6	247	1.63	76	15	9
U-7	7.0	13.7	0.91	15.0	7.9	192	1.52	56	28	16
U-8	6.7	12.9	0.96	13.4	8.3	201	1.42	53	29	18
U-9	6.9	11.3	0.95	11.9	5.8	153	1.57	56	23	21
U-10	6.9	8.9	0.76	11.7	6.9	173	1.47	58	26	16
Mean	**6.9**	**12.7**	**0.92**	**13.7**	**7.6**	**205**	**1.49**	**55**	**29**	**16**

Note: P data for mid-field of Weekoty are lacking.

Table 3.5. Mean values of soil data for extensive fields.

Field	pH	Org C	N	C:N	AvP	TotP	Bulk Den.	Sand	Silt	Clay
		(g/kg)			(mg/kg)		(g/cm3)		(%)	
Cultivated										
NC1	7.2	7.1	0.67	10.4	13.4	279	1.48	69	17	14
NC2	7.4	17.9	1.03	17.3	8.3	309	1.50	37	38	25
NC3	7.7	6.8	0.64	10.6	6.0	303	1.40	65	20	15
PC1	6.3	13.0	0.92	14.2	12.6	203	1.56	62	23	15
PC2	6.7	11.8	0.93	12.5	11.0	308	1.55	57	29	14
PC3	7.0	10.5	0.87	12.3	13.9	295	1.52	64	23	14
BC1	7.1	10.7	0.84	12.5	6.5	174	1.38	56	25	19
BC4	7.2	14.4	0.90	16.1	9.1	400	1.48	33	36	31
BC5	6.6	13.6	1.04	13.0	8.3	377	1.41	61	26	13
Abandoned										
NA1	7.3	16.8	1.26	13.4	15.9	337	1.47	21	49	30
NA2	7.2	7.4	0.69	10.5	9.2	306	1.46	45	30	25
NA3	6.8	13.1	1.14	11.1	18.3	304	1.52	48	31	21
PA1	6.7	17.6	1.37	12.9	15.7	384	1.56	27	42	31
PA2	6.9	9.4	0.72	13.0	8.0	297	1.46	46	36	18
PA3	6.4	19.4	1.48	13.1	13.5	339	1.51	34	41	25
BA1	6.4	12.9	0.95	13.6	7.1	230	1.41	52	31	18
BA2	7.0	12.6	0.97	13.0	11.1	244	1.35	65	20	15
BA3	7.2	9.5	0.85	11.2	9.8	284	1.36	45	36	19
BA4	6.5	16.5	1.19	13.8	5.7	233	1.45	63	26	11
Uncultivated										
NU1	6.9	13.4	0.96	14.0	11.8	390	1.51	26	44	30
NU2	7.1	18.3	1.30	14.1	16.5	425	1.42	43	34	23
NU3	7.2	9.4	0.67	13.7	12.4	302	1.42	56	22	22
PU1	7.0	9.9	0.91	10.9	6.4	239	1.53	28	35	38
PU2	6.8	7.0	0.63	11.1	5.6	192	1.48	52	32	16
PU3	6.7	14.7	1.08	13.7	11.3	229	1.30	61	24	16
BU1	6.5	17.3	1.28	13.5	12.8	399	1.36	47	34	18
BU2	5.9	10.7	0.77	13.7	12.8	449	1.45	66	23	11
BU3	6.8	20.6	1.33	15.1	20.5	356	1.37	47	32	21
BU4	6.3	9.8	0.93	10.2	9.3	234	1.48	59	27	14

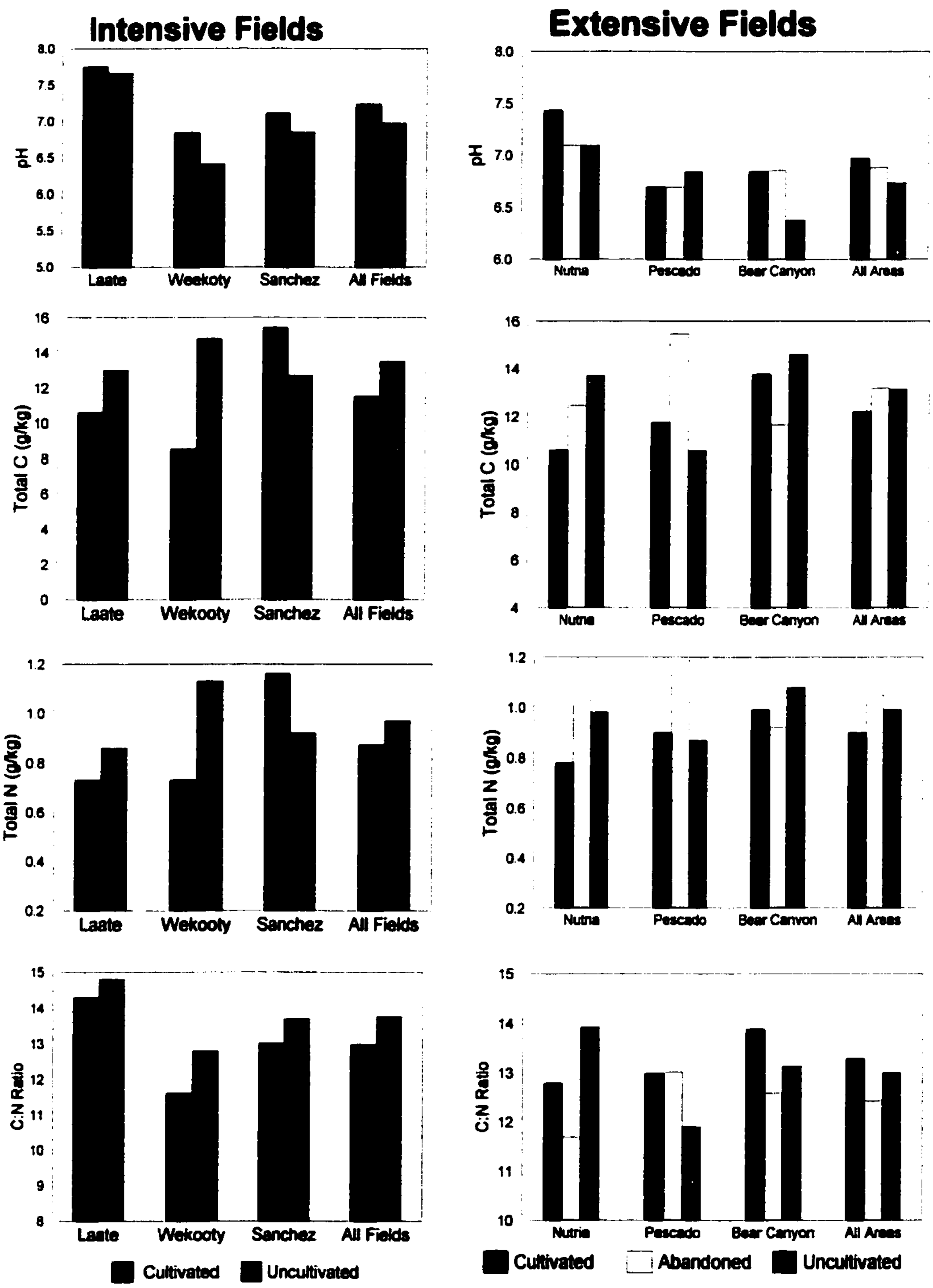


Figure 3.11. Comparison of pH, C, N, and C:N ratios in intensive and extensive fields.

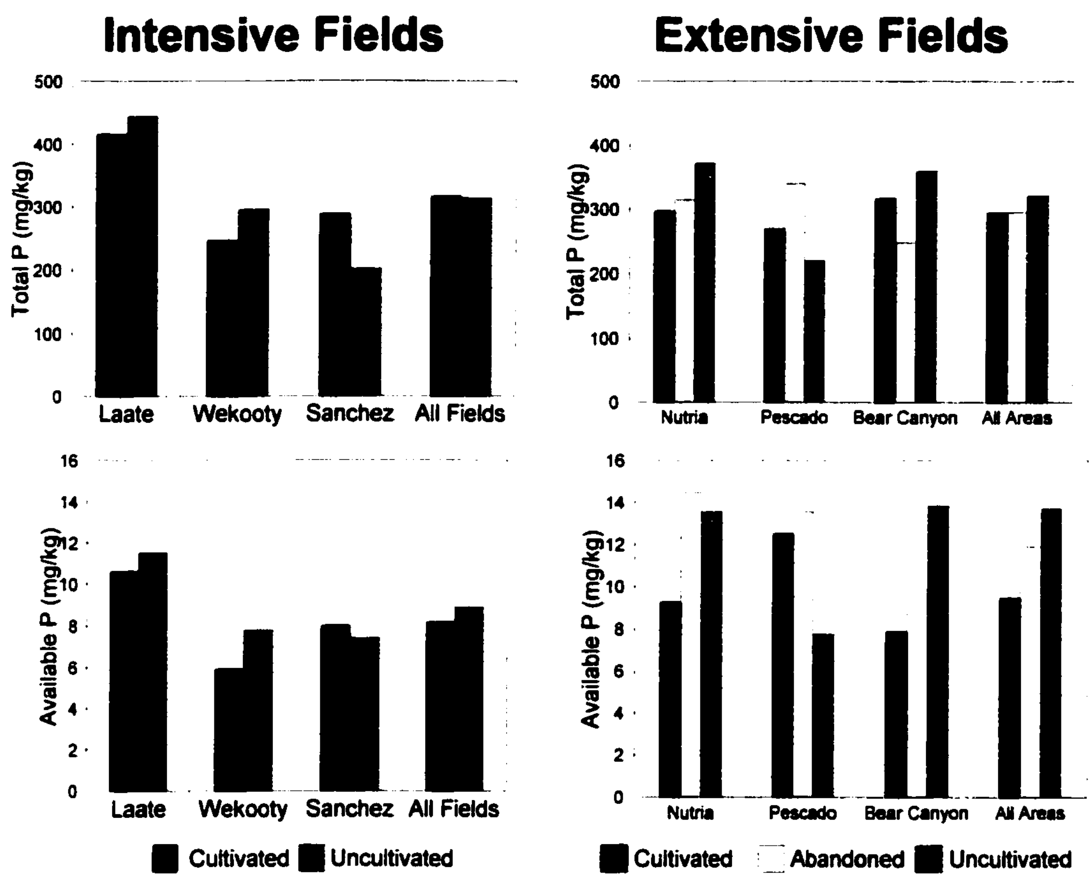


Figure 3.12. Comparison of total and available P in intensive and extensive fields.

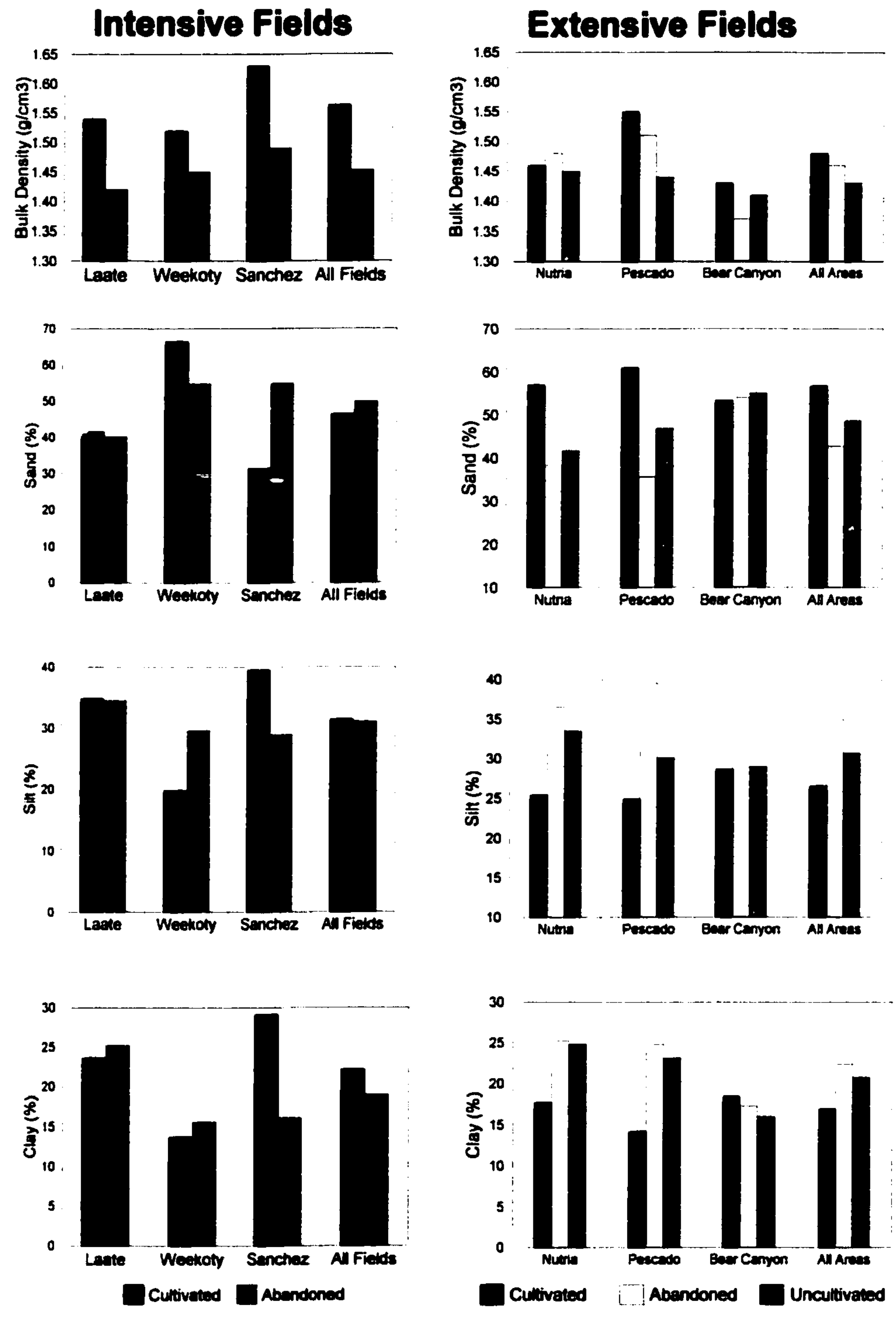


Figure 3.13. Comparison of bulk density and soil texture in intensive and extensive fields.

Table 3.6. *t*-tests for intensive fields.

Soil Property		Field	Mean for Each Field		Mean for All Fields		% Diff. of	P-value	Significance
			Cult	Uncult	Cult	Uncult	Cult. Fields		
pH		Laate	7.75	7.68	7.24	6.98	--	0.14	*
		Weekoty	6.85	6.40					
		Sanchez	7.11	6.85					
Organic C	(g/kg)	Laate	9.99	12.54	11.28	13.34	-18.3	0.52	
		Weekoty	8.46	14.83					
		Sanchez	15.38	12.66					
N	(g/kg)	Laate	0.74	0.86	0.87	0.97	-11.1	0.10	*
		Weekoty	0.73	1.13					
		Sanchez	1.16	0.92					
C:N Ratio		Laate	13.53	14.23	12.71	13.58	-6.8	0.04	*
		Weekoty	11.60	12.83					
		Sanchez	13.00	13.67					
Available P	(mg/kg)	Laate	10.87	11.81	8.35	9.11	-9.1	0.41	
		Weekoty	5.97	7.92					
		Sanchez	8.20	7.60					
Total P	(mg/kg)	Laate	427.21	457.71	324.31	321.06	1.0	0.95	
		Weekoty	249.73	300.48					
		Sanchez	296.00	205.00					
Bulk Density	(g/cm3)	Laate	1.54	1.42	1.56	1.45	7.6	0.03	*
		Weekoty	1.52	1.45					
		Sanchez	1.63	1.49					
Sand	(%)	Laate	41.52	40.21	46.47	49.99	-7.6	0.77	
		Weekoty	66.49	54.77					
		Sanchez	31.40	55.00					
Silt	(%)	Laate	34.81	34.54	31.37	31.02	-1.1	0.96	
		Weekoty	19.81	29.62					
		Sanchez	39.50	28.90					
Clay	(%)	Laate	23.63	25.23	22.14	18.98	16.6	0.59	
		Weekoty	13.69	15.61					
		Sanchez	29.10	16.10					

* - significant at 0.2; note: % difference of pH not shown due to log scale of values

Table 3.7. ANOVA for intensive fields.

Field		Cultivated Mean	Cultivated St. Dev.	Uncultivated Mean	Uncultivated St. Dev.	% Diff. Of Cult. Fields	F	P-value	Significance
Laate									
pH		7.75	0.05	7.68	0.19		1.22	0.284	
Organic C	(g/kg)	10.00	1.36	12.54	4.42	-25.4	3.03	0.099	
N	(g/kg)	0.74	0.06	0.86	0.23	-17.4	3.01	0.100	
C:N Ratio		13.53	0.95	14.23	2.13	-5.2	0.91	0.354	
Available P	(mg/kg)	10.87	1.11	11.81	3.37	-8.7	0.70	0.413	
Total P	(mg/kg)	427.21	31.52	457.71	39.94	-7.1	3.59	0.074	
Bulk Density	(g/cm3)	1.54	0.04	1.42	0.07	8.3	23.56	0.000	***
Sand	(%)	41.52	5.54	40.21	9.87	3.3	0.13	0.719	
Silt	(%)	34.81	4.20	34.54	7.64	0.8	0.01	0.920	
Clay	(%)	23.63	1.73	25.23	2.84	-6.8	2.32	0.145	
Weekoty, Field Edge									
pH		6.85	0.31	6.40	0.27		12.27	0.003	**
Organic C	(g/kg)	8.46	1.69	14.83	6.72	-75.3	8.45	0.009	**
N	(g/kg)	0.73	0.14	1.13	0.42	-55.8	8.41	0.010	**
C:N Ratio		11.60	0.39	12.83	0.87	-10.6	16.68	0.001	***
Available P	(mg/kg)	5.43	2.98	7.20	4.48	-32.6	1.19	0.289	
Total P	(mg/kg)	249.73	17.19	300.48	53.63	-20.3	8.12	0.011	*
Bulk Density	(g/cm3)	1.52	0.05	1.45	0.06	5.2	8.36	0.010	**
Sand	(%)	66.49	1.77	54.77	10.81	21.4	11.45	0.003	**
Silt	(%)	19.81	2.17	29.62	7.93	-49.5	14.26	0.001	**
Clay	(%)	13.69	1.68	15.61	3.86	-14.0	2.08	0.166	
Weekoty, Middle Field									
pH		7.18	0.28	6.40	0.27		40.38	0.000	***
Organic C	(g/kg)	9.59	2.95	14.83	6.72	-54.6	5.10	0.037	*
N	(g/kg)	0.77	0.23	1.13	0.42	-48.0	5.89	0.026	*
C:N Ratio		12.52	0.69	12.83	0.87	-2.5	0.78	0.389	
Bulk Density	(g/cm3)	1.53	0.04	1.45	0.06	5.5	9.86	0.006	**
Sand	(%)	67.23	3.20	54.77	10.81	22.7	12.22	0.003	**
Silt	(%)	20.85	2.27	29.62	7.93	-42.1	11.32	0.003	**
Clay	(%)	11.91	1.74	15.61	3.86	-31.1	7.65	0.013	*
Sanchez									
pH		7.11	0.25	6.85	0.18		7.12	0.002	**
Organic C	(g/kg)	15.38	6.19	12.66	6.00	21.5	1.00	0.331	
N	(g/kg)	1.16	0.36	0.92	0.40	26.5	2.03	0.171	
NO3-N	(mg/kg)	9.59	4.79	4.95	6.89	93.7	3.06	0.097	
NH4-N	(mg/kg)	15.14	3.08	10.30	2.04	47.0	17.17	0.001	***
C:N Ratio		13.00	1.84	13.67	1.53	-5.2	0.79	0.387	
Available P	(mg/kg)	8.24	2.51	7.56	1.85	9.0	2.24	0.514	
Total P	(mg/kg)	295.50	50.61	205.00	32.19	44.1	21.10	0.000	***
Bulk Density	(g/cm3)	1.63	0.07	1.49	0.10	9.9	14.19	0.001	**
Sand	(%)	31.50	6.77	55.00	11.94	-74.6	29.58	0.000	***
Silt	(%)	39.50	4.95	28.90	9.39	36.7	9.98	0.005	**
Clay	(%)	29.10	2.60	16.10	3.84	80.7	78.48	0.000	***

* - significant at 0.05; ** - significant at 0.01; *** - significant at 0.001

Note: % difference of pH not shown due to log scale of values

Table 3.8 ANOVA tests for extensive fields.

Field		Cultivated		Abandoned		Uncultivated		Treatment	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	P-value	Signif.
pH		7.00	0.9	6.90	0.4	6.70	1.0	0.17	
Organic C	(g/kg)	12.20	4.9	13.20	5.5	13.10	6.6	0.65	
N	(g/kg)	0.90	0.3	1.05	0.4	0.99	0.4	0.24	
C:N Ratio		13.30	2.3	12.40	1.3	13.00	2.5	0.71	
Available P	(mg/kg)	9.50	4.8	11.90	5.3	13.70	5.2	0.46	
Total P	(mg/kg)	294.00	72.0	296.00	50.0	322.00	94.0	0.64	
Bulk Density	(g/cm3)	1.48	0.1	1.46	0.1	1.43	22.0	0.32	
Sand	(%)	56.70	1.9	42.60	16.0	48.60	16.0	0.13	
Silt	(%)	26.50	26.5	35.00	10.3	30.70	9.4	0.08	
Clay	(%)	16.90	8.3	22.40	6.9	20.80	8.9	0.30	

found in organic C by the paired *t*-test for the paired fields as whole, even though cultivated fields average less 18% organic C (relative difference, as with percentages given in Tables 3.6 and 3.7) than uncultivated ones. Although a mean 18% difference was found, there is high variability between fields, and one of the intensive cultivated fields, Sanchez, actually had an increase of 22% in organic C, while the Latte field, Weekoty field edge, and Weekoty middle field, had decreases of 25%, 75%, and 55%, resectively. The only statistically significant differences were found in the Weekoty field. The increase is probably explained by its higher clay content (29% vs. 16%) and lower sand content (31% vs. 55%). No such textural differences exist in the other two intensive fields. It is worth noting that because of increased bulk density levels (as discussed below), the total amount of C in the 0-15 cm level is not reduced as much if adjustments are made for bulk density differences (that is, on a weight/volume rather than weight/weight basis for comparing concentrations).

No significant differences in organic C were found among treatments in the extensive fields. Cultivated soils averaged 12.2 g/kg, which is slightly higher than the 13.2 g/kg, and 13.1 g/kg of the abandoned and uncultivated fields, respectively. The lack of consistent differences is manifested by a great deal of overlap in organic C levels of the extensive treatments.

Trends in N are similar to those of organic C data, which is not surprising given that both generally accompany a decline in organic matter. The paired *t*-tests indicate that cultivated soils average 11% less organic C than uncultivated references. The presence or lack of statistical differences in N mirror those of organic C in the ANOVA tests for all intensive fields, and no statistical differences were found between fields in the extensive treatment. Nitrate- and ammonium-N determinations were obtained for the Sanchez field, using data obtained from Norton's thesis research (Norton 1996). These results showed increases of over 90% and nearly 50%, respectively, in the cultivated field, which is an interesting finding. Because these plant-available forms of N may vary in concentration over short time intervals, it is uncertain if this is a trend that would be repeated with further work. Plant available N varies from season to season, year to year, and with unique management histories of different fields.

The paired *t*-test showed that intensive cultivated soils as a whole have significantly lower C:N ratios, with a mean difference of about 5%. The only statistically significant differences in individual intensive field comparisons, however, were found in the Weekoty field. Decreased C:N ratios indicate greater organic matter decomposition, a trend that is commonly found in cultivated soils. Many modern cultivated soils have narrower ratios than comparable uncultivated soils (Jenny 1941; Sandor et al. 1986). No statistical differences in C:N ratio were found between the treatments of extensive fields, and, in fact, the cultivated soils had higher ratios than the other two treatments.

No definitive trends were found in available and total P data from both the intensive and extensive fields. Soils of intensive cultivated fields averaged 9% less available P and 1% more total P, but neither of these values were statistically significant. There were no consistent changes in total and available P for the three intensive fields. Total P is significantly higher in the cultivated Sanchez field, but again, this increase is probably chiefly a function of the higher clay content. Similar to organic C and N, available and total P are slightly reduced in the cultivated soils of the Laate and Weekoty fields. Available P is lower in the extensive cultivated soils, but, again, not levels of deficiency and not at a level that is statistically significant. Phosphorus requirements for crops are not well understood for many soils of the Southwest, but available phosphorus levels below 2 mg/kg (or 2 ppm) are usually considered low, and values above 5 mg/kg are considered sufficient (Doerge 1985). Because all Zuni samples exceed 5 mg/kg, often by a factor of two, there is no indication that available P is low in the Zuni runoff soils.

Of all soil data compiled by this study, bulk density in the cultivated intensive fields showed the strongest anthropogenic influence. On average, bulk density is 7.8% higher in the intensive cultivated soils (1.56 vs. 1.45 g/cm^3) as whole. For each intensive field, the increased bulk density levels are 8.3%, 5.2%, 5.5%, and 9.9%, for the Laate, edge and middle of Weekoty, and Sanchez fields. The greatest change is for the cultivated Sanchez field, which has a mean bulk density of 1.64 g/cm^3, with individual samples ranging from 1.55 to

1.74 g/cm^3. Bulk densities in the range of 1.55 to 1.80 g/cm^3 may impede root growth, depending on soil texture (Wild 1993:117). In the sandy loams and loams so widespread in the Zuni soils, we would not expect a mean 8.5% increase to be clearly indicative of degradation, and there may actually be a benefit if soil moisture is increased. In lab and field studies of compacted clays, maize growth and productivity highly correlated to compaction levels in the bulk density range of 0.94 to 1.30 g/cm^3 (Phillips and Kirkham 1962a, 1962b). If compaction continues in the Zuni soils, maize root penetration and seedling emergence could be impeded at levels that would limit agricultural productivity. Such an outcome at Zuni seems unlikely for the textures and consistence of most Zuni agricultural soils. Because the predominantly sandy loam and loam topsoils are generally friable to very friable, there is no indication that compaction limits seedling emergence. Compaction problems are more likely when plowing wet soils (Soane 1980), which is not a concern when soils are plowed in the semiarid Zuni area. Furthermore, Zuni farmers do not recognize soil compaction as a degradational effect on agricultural productivity. Unlike agricultural systems in wetter climates, compaction at the levels found in the Zuni soils may actually be beneficial for agricultural production because of greater moisture retention. Additional data on agricultural yields and pore continuity and size distributions are needed to test the possible that compaction is beneficial.

There were no statistical differences in bulk density between treatments of the extensive fields (see Figure 3.8). Bulk density differences averaged only 3.5% in the cultivated versus uncultivated fields (1.48 vs. 1.43 g/cm^3), so compaction does not appear to be a widespread effect in the eastern part of the Zuni Reservation at this broader scale of analysis. There is simply a high degree of overlap between treatments at the much broader, extensive scale of analysis. The only extensive fields that may have compaction problems are in the Pescado study area (see Figure 3.13).

Paired *t*-tests for the intensive fields identified no statistically significant differences between percentages of sand, silt, and clay. Absolute percentage changes in cultivated intensive fields as a whole were 3.5% less sand, 4% more clay, and no change in silt content. Size separates were very similar for the Laate field. Cultivated Weekoty soils have, on average, 13% more sand, 9% less silt, and 4% less clay. By contrast, the cultivated Sanchez field has about 24% less sand, 11% more silt, and 13% more clay. These textural differences actually reflect a combination of natural horizontal variability overprinted by recent natural and culturally modified sedimentation processes in the cultivated fields. Because of this confounding factor, it is often impossible to adequately hold the non-anthropogenic factors sufficiently constant for evaluating cultivation effects. Soil texture, because of its strong effect on nutrient concentrations and nutrient-holding properties, is a crucial variable in identifying and interpreting changes in the nutrient status of cultivated soils.

The extensive fields, because of the much larger sample size, may be a much better way to assess anthropogenic influences on soil separates, but this assumes that we have a representative, or at least a near representative, sample of fields. No statistical differences were identified by the ANOVA tests of treatment effects. An examination of soil texture in the extensive fields is not easily interpretable, however, because the percentages of sand, silt, and clay of the uncultivated fields are intermediate between the cultivated and abandoned fields, so there are no consistent trends along gradients of farming intensity (based on mechanical plowing being the most intensive, uncultivated treatments the least, and abandoned fields intermediate).

MANOVA tests indicate that there are no overall treatment differences for the extensive fields. The following probability values were obtained for the different F statistics: Wilk's lambda ($P>F = 0.23$), Pillai's Trace ($P>F = 0.22$), Hotelling-Lawley Trace ($P>0.24$), and Roy's Greatest Root ($P>F= 0.07$). The latter measure is nearly significant at the 0.05 level.

Posteriori tests of other potential sources of variability between treatments were conducted for the extensive fields. Posteriori blocks consisted of landform (alluvial fans versus colluvial footslopes), landscape positions (within versus outside of canyon), and groupings of fields with high versus low amounts of clay and sand. No statistical differences were found by the posteriori tests (at the 0.05 level of significance) for both treatment effects and study area by treatment interactions. The greatest treatment difference was found for pH ($P>F = 0.09$). The lack of statistical differences for some variables, especially pH, may be a function of small sample sizes for the posteriori blocks. To ensure a sufficient sample size for testing the effects of factors that may explain the treatment effects, future studies should consider blocking on landform, soil texture, or other potentially important factors in their initial stratified sampling design.

Correlation analyses were undertaken to assess the relationships between soil test variables (Tables 3.9 and 3.10). This analysis focused on comparisons between the chemical and physical tests to search for connections between these variables. Not surprisingly, there

Table 3.9. Correlation between chemical and physical properties for intensive fields.

Comparison	Laate		Weekoty		Sanchez	
	Cult	Uncult	Cult	Uncult	Cult	Uncult
OC vs. Sand	-0.95 **	-0.79 **	0.19	0.91 **	-0.50	-0.84 **
OC vs. Silt	0.94 **	0.77 **	0.13	0.84 **	0.72 **	0.88 **
OC vs. Clay	0.74 **	0.67 *	-0.37	0.84 **	-0.07	0.46
OC vs. Bulk Density	-0.34	-0.59 *	0.51	-0.22	-0.74 **	-0.86 **
N vs. Sand	-0.87 **	-0.72 *	0.20	-0.89 **	-0.62 *	-0.85 **
N vs. Silt	0.88 **	0.71 *	0.13	0.81 **	0.79 **	0.85 **
N vs. Clay	0.65 *	0.58 *	-0.37	0.84 **	0.10	0.56 *
N vs. Bulk Density	-0.29	-0.43	0.59 *	-0.24	-0.71 **	-0.88 **
Av.P vs. Sand	-0.41	-0.22	-0.15	-0.68 *	-0.43	-0.25
Av.P vs. Silt	0.31	0.23	0.42	0.60 *	0.64 *	0.34
Av.P vs. Clay	0.56 *	0.15	-0.39	0.67 *	-0.10	-0.07
Av.P vs. Bulk Density	0.40	0.09	-0.07	-0.14	-0.78 **	-0.57
P vs. Sand	-0.81 **	-0.68 *	-0.26	-0.86 **	0.43	0.10
P vs. Silt	0.81 **	0.63 *	0.40	0.77 **	-0.31	0.14
P vs. Clay	0.62 *	0.66 *	0.25	0.84 **	-0.53	-0.65 *
P vs. Bulk Density	-0.09	-0.27	0.47	-0.25	0.27	-0.23

* Significant at $\alpha = 0.05$; ** Highly significant at $\alpha = 0.01$

Table 3.10. Correlation between chemical and physical soil properties for extensive fields.

Comparison	Cultivated	Abandoned	Uncultivated
OC vs. Sand	-0.78 **	-0.38	-0.16
OC vs. Silt	0.88 **	0.42	0.26
OC vs. Clay	0.58	0.31	0.05
OC vs. Bulk Density	0.30	0.50	-0.61 *
N vs. Sand	-0.51	-0.45	-0.22
N vs. Silt	0.69 *	0.46	0.32
N vs. Clay	0.25	0.40	0.11
N vs. Bulk Density	0.29	0.58 *	-0.52
Av.P vs. Sand	0.34	-0.60 *	0.08
Av.P vs. Silt	-0.32	0.53	-0.01
Av.P vs. Clay	-0.32	0.68 *	-0.13
AvP vs. Bulk Density	0.77 **	0.60 *	-0.54
P vs. Sand	-0.41	-0.89 **	-0.12
P vs. Silt	0.43	0.79 **	-0.08
P vs. Clay	0.34	0.91 **	0.21
P vs. Bulk Density	-0.01	0.75 **	-0.05

* Significant at $\alpha = 0.05$; ** Highly significant at $\alpha = 0.01$

are many statistically significant positive and negative correlations. Several of these connections have already been reviewed in the discussion above, without quantifying them. Here, we focus on two correlations (organic C vs. bulk density and organic C vs. silt) that have been examined by previous studies. Scatter plots for both the means and individual samples of the 29 extensive fields are depicted in Figures 3.14 and 3.15. Many studies have shown that organic C and bulk density are inversely related. That is, as organic C declines, bulk density increases (e.g., (Sandor, et al. 1986). Statistically significant inverse correlations were only found in the cultivated and uncultivated soils of the Weekoty field, and the uncultivated extensive soils. These data show that bulk density and organic C are not related in a way that is predictable in fields influenced by historic agriculture. Surprisingly, the correlations between bulk density and organic C are positive for cultivated and abandoned soils, though not at statistically significant levels, and we might not have expected this relationship. The lack of statistically significant differences is likely affected by variable degrees of sedimentation for the different alluvial fans sampled.

Correlations between organic C and silt are correlated at statistically significant levels in many cultivation contexts, even more so than for organic C and clay which is a common attribute of most agricultural systems. This finding supports the interpretation of co-sedimentation of organic matter and silt in the depositional systems of Zuni runoff fields. This important trend was first identified in Norton's thesis research of the Sanchez field (Norton 1996), and the much larger data base presented here further demonstrates this important process in nutrient renewal of Zuni runoff fields.

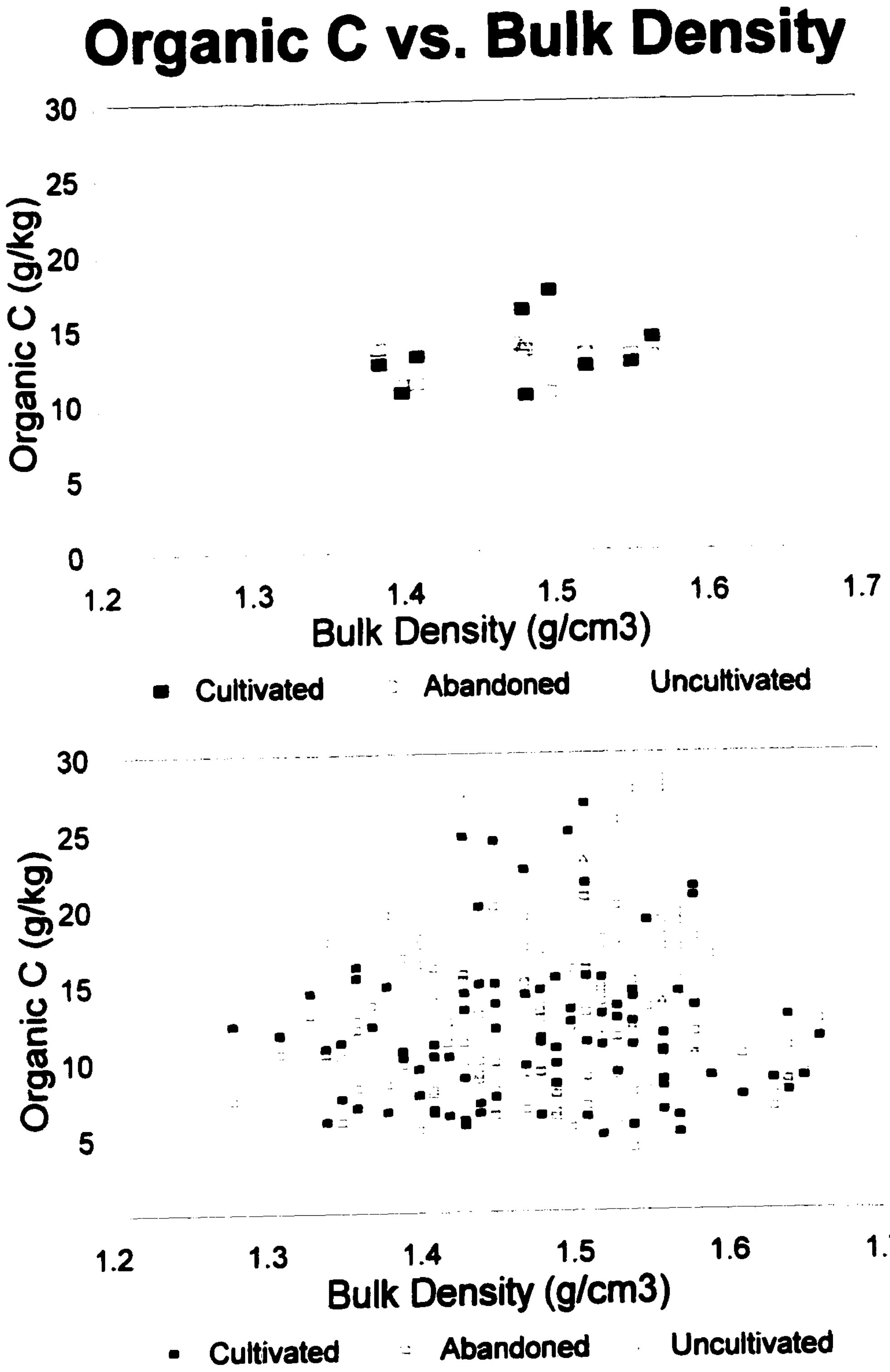
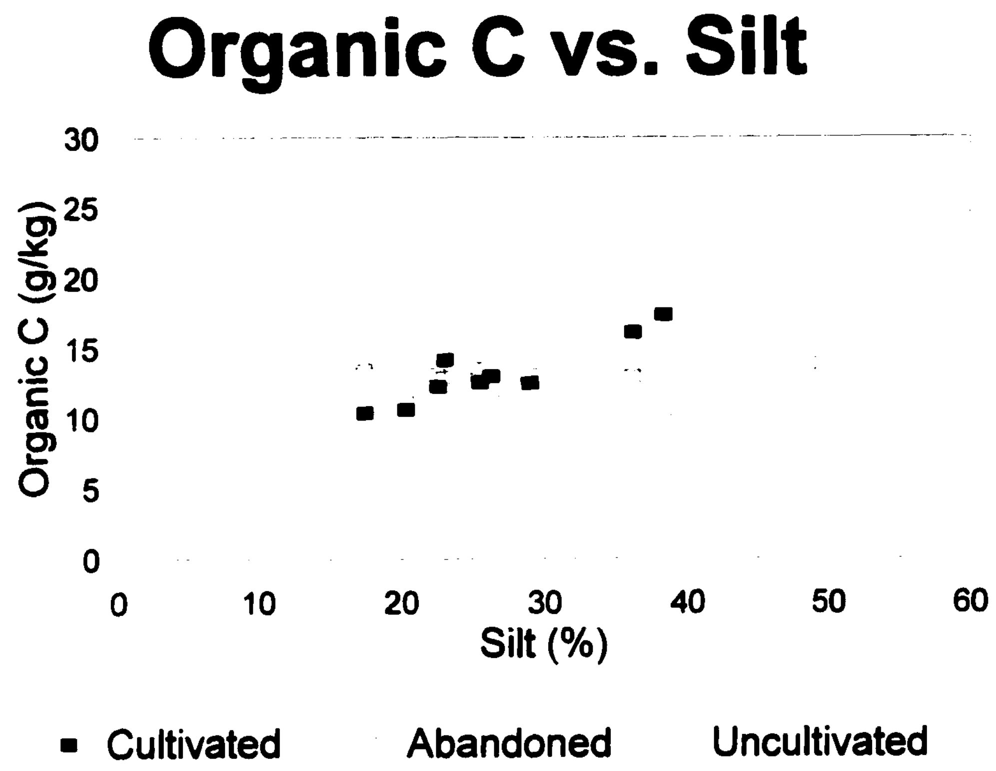


Figure 3.14. Scatter plots of organic C versus bulk density for extensive fields (top shows field means and bottom shows the values for all individual samples).



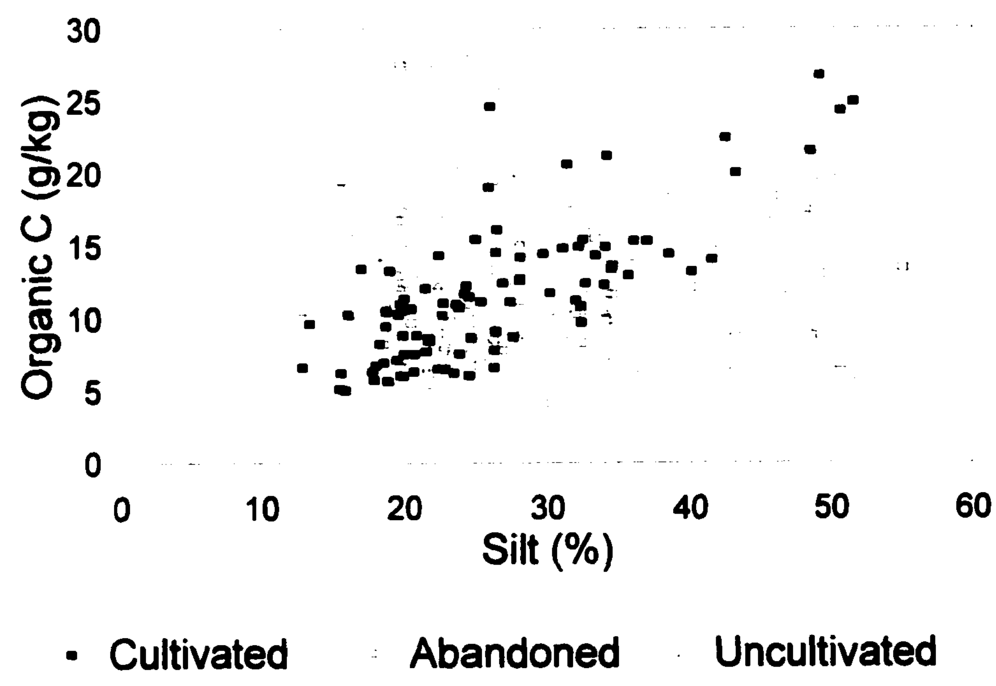


Figure 3.15. Scatter plots of organic C versus silt for extensive fields (top shows field means and bottom shows the values for all individual samples).

CONCLUSIONS

We did not find evidence that Zuni agricultural soils are degraded. Our data indicate that cultivation has had both positive and negative effects on agricultural soils. Beneficial effects include thickened A horizons and organic matter coatings on grains and granular peds in many cultivated fields. Paired cultivated soils have higher bulk densities and pH levels, and either reduced or enriched levels of N and organic C. Although these differences are often statistically significant, they are not great enough to indicate degradation of agricultural runoff soils.

Soil texture has such a strong effect on nutrient-holding properties that it is an especially important variable in interpreting soil nutrient status. Textural differences between cultivated and uncultivated contexts actually reflect a combination of natural horizontal and vertical variability on alluvial fans that has been overprinted by natural and cultural sedimentation processes in cultivated fields. This situation highlights a potential major problem with the paired-field approach, and that is why we also included an extensive component in the study.

In attempting to evaluate anthropogenic effects on soil texture and other variables, it is often difficult to impossible to adequately hold the non-anthropogenic factors constant, or at least approximately so, when there is so much natural variability over short distances. Consequently, the risk of psuedoreplication in a sampling design is always present in this type of field study. Psuedoreplication can result from collecting soil samples that differ because of factors other than anthropogenic treatments alone. Paired field comparisons assume that the uncultivated samples are valid controls, but this assumption very often may not be met. Indeed, the biggest challenge in this type of research is finding valid uncultivated samples to serve as controls for gauging anthropogenic influences. For studies limited to small sample sizes (those with less than about 100 samples), the paired-site method is probably still the best approach, but larger studies should incorporate both paired and unpaired sampling methods.

Statistical analysis of extensive fields failed to identify significant treatment (cultivated, abandoned, and uncultivated) effects, which strongly supports the hypothesis that soil alterations are not at levels indicative of degradation. A few slight trends were found among treatments (e.g., a 3.5% increase in bulk density of cultivated soils), but differences among study areas were of greater magnitude. The only significant statistical differences in the extensive data set were found between study units, and these differences were only in pH and bulk density. Even so, the magnitude of these differences (due mainly to variability in soil parent material) is low.

In conclusion, there is no clear indication that agricultural runoff soils are degraded. Cultivated soils in paired fields often appear to be more degraded, but many of the differences are explained by natural variability in texture rather than anthropogenic influences. The lack of statistical differences and the low magnitude of soil changes in unpaired fields strongly supports our interpretation that agricultural soils are not degraded by cultivation.

REFERENCES

Anderson, O. J., S. G. Lucas, D. W. Love and S. M. Cather (editors)
1989 *Southeastern Colorado Plateau: New Mexico Geological Society Fortieth Annual Field Conference, September 28-October 1, 1989*. New Mexico Geological Society, Inc., Socorro.

Arrhenius, O.
1963 Investigation of Soil from Old Indian Sites. *Ethnos* 28:122-136.

Arshad, M. A. and G. M. Coen
1992 Characterization of Soil Quality: Physical and Chemical Criteria. *American Journal of Alternative Agriculture* 7:25-31.

Blake, G. R. and K. H. Hartge
1986 Bulk Density. In *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods.*, edited by A. Klute, pp. 363-375. vol. No. 9. American Society of Agronomy and Soil Science Society of America, Madison.

Boers, T. M. and J. Ben-Asher
1982 A Review of Rainwater Harvesting. *Agricultural Water Management* 5:145-158.

Bruins, H. J.
1986 *Desert Environment and Agriculture in the Central Negev and Kadesh-Barnea During Historical Times*. MIDBAR Foundation, Nijkerk, The Netherlands.

1990 Ancient Agricultural Terraces at Nahal Mitnan. *Atiqot* 10:10-28.

Bruins, H. J., M. Evenari and A. Rogel
1987 Run-off Farming Management and Climate. In *Progress in Desert Research*, edited by L. B. a. M. G. Wurtele, pp. 3-14. Rowman & Littlefield, Totawa, New Jersey.

Bryan, K.
1929 Flood-Water Farming. *The Geographical Review* 19:444-456.

Cohen, I. S., V. L. Lopes, D. C. Slack and C. H. Yanez
1995 Assessing Risk for Water Harvesting Systems in Arid Environments. *Journal of Soil and Water Conservation* 50(5):446-449.

Cressie, Noel
1990 The Origins of Kriging. *Mathematical Geology* 22(3): 239-252.

1991 *Statistics for Spatial Data*. John Wiley & Sons, New York.

Cushing, F. H.
1979 *Zuni: Selected Writings of Frank Hamilton Cushing*. University of Nebraska Press, Lincoln.

Damp, J. E. and J. W. Kendrick
2000 Zuni Emergent Agriculture: Early Irrigation on the Colorado Plateau. Paper presented at the Southwest Symposium, Santa Fe, New Mexico.

Dick, W. A. and M. A. Tabatabai
1977 An Alkaline Oxidation Method for Determination of Total Phosphorus in Soils. *Soil Science Society of America Journal* 41(3):511-514.

Doolittle, W. E.
1984 Cabeza de Vaca's Land of Maize: An Assessment of Its Agriculture. *Journal of Historical Geography* 10:246-262.

Dregne, H. E.
1963 Soils of the Arid West. In *Aridity and Man: The Challenge of the Arid Lands in the United States*, edited by C. Hodge and P. C. Duisberg, pp. 215-238. Publication No. 74. American Association for the Advancement of Science, Washington.

Evenari, M., L. Shanan and N. H. Tadmor
1982 *The Negev: The Challenge of a Desert*. 2nd ed. Harvard University Press, Cambridge.

Fenton, T. E., J. R. Brown and M. J. Mausbach
1999 Effects of Long-Term Cropping on Organic matter Content of Soils: Implications for Soil Quality.

Ferguson, T. J. and E. R. Hart
1985 *A Zuni Atlas*. The Civilization of the American Indian Series No. 172. University of Oklahoma Press, Norman.

Gee, G. W. and J. W. Bauder
1986 Particle-size Analysis. In *Methods of Soil Analysis. Physical and Mineralogical Methods*, edited by A. Klute, pp. 383-411. 2nd ed. vol. Monograph No. 9, Part 1. American Society of Agronomy and Soil Science Society of America, Madison.

Golden Software, Inc.
1999 *Surfer User's Guide: Contouring and 3D Surface Mapping for Scientists and Engineers*. Golden Software, Inc., Golden, Colorado.

Graham, M.
1990 *Report on Documented Twentieth Centruy Irrigated Agricultural Fields on the Zuni Reservation*. Submitted to Preliminary Report of the Water II Project, Zuni Archaeology Program for the Institute of the NorthAmerican West.

Hack, J. T.
1942 *The Changing Physical Environment of the Hopi Indians of Arizona*. Papers of the Peabody Museum of American Archaeology and Ethnography No. 35. Peabody Museum, Cambridge.

Homburg, J. A.
1994 Soil Fertility in the Tonto Basin. In *Changing Land-use Practices in the Tonto Basin*, edited by R. Ciolek-Torrello and J. R. Welch, pp. 253-295. Technical Series No. 28. vol. 3: Fieid Study. Statistical Research, Tucson.

Homburg, J. A. and J. A. Sandor
1997 An Agronomic Study of Two Classic Period Agricultural Fields in the Horseshoe Basin. In *Vanishing River: Landscapes and Lives of the Lower Verde Valley. The Lower Verde Archaeological Project*, edited by J. A. Homburg and R. Ciolek-Torrello, pp. 127-148. vol. 2: Agricultural, Subsistence, and Environmental Studies. SRI Press, Tucson.

Hurlbert, S. H.
1984 Pseudoreplication and the Design of Ecological Field Experiments. *Ecological Monographs* 54(2):187-211.

International Soil Science Society
1985 *Handbook for Soil Thin Section Description*. Waine Research, Woverhampton.

Karlen, D. L., M. J. Mausbach, J. W. Doran, R. G. Cline, R. F. Harris and G. E. Schuman
1996 Soil Quality: Concept, Rationale, and Research Needs. *Soil Science Society of America* 60.

Kimble, J. M.
1998 Minimum Data Sets Needed for Soil and Climatic Characterization. In *Soil Quality and Agricultural Sustainability*, edited by R. Lal, pp. 44-50. Ann Arbor Press, Chelsea, Michigan.

Kintigh, K. W.
1985 *Settlement, Subsistence, and Society in Late Zuni Prehistory*. The University of Arizona Press, Tucson.

Kowsar, A.
1991 Floodwater Spreading for Desertification Control: An Integrated Approach. An Iranian Contribution to the Implementation of the Plan of Action to Combat Desertification. *Desertification Bulletin* 19:3-18.

Larson, W. E. and F. J. Pierce
1991 Conservation and Enhancement of Soil Quality. In *Evaluation for Sustainable Land Management in the Developing World*, pp. 175-203. vol. 2: Technical Papers. International Board for Soil Resource and Management, Bankok.

Larson, W. E. and F. J. Pierce
1994 The Dynamics of Soil Quality as a Measure of Sustainable Management. In *Defining Soil Quality for a Sustainable Environment*, edited by J. W. Doran, D. C. Coleman, D. F. Bezdicek and B. A. Stewart, pp. 37-51. Soil Science Society of America and American Society of Agronomy, Madison.

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

Loomis, R. S. and D. J. Connor
1992 *Crop Ecology: Productivity and Management in Agricultural Systems.* Cambridge University Press, Cambridge.

Lowrance, R.
1992 Sustainable Agriculture Research at the Watershed Scale. *Journal of Sustainable Agriculture* 2(3):105-111.

Ludwig, J. A.
1987 Primary Productivity in Arid Lands: Myths and Realities. *Journal of Arid Environments* 13:1-7.

Matheron, G.
1962 *Traité de geostatique appliquée.* Vol I: Memoires du Bureau de Recherches Géologiques et Miniéres, No. 14. Editions Technip, Paris.

Mausbach, M. J. and C. A. Seybold
1998 Assessment of Soil Quality. In *Soil Quality and Agricultural Sustainability*, edited by R. Lal, pp. 33-43. Ann Arbor Press, Chelsea, Michigan.

McGee, W. J.
1895 Beginnings of Agriculture. *American Anthropologist* 8:350-375.

McLean, E. O.

1982 Soil pH and Lime Requirements. In *Methods of Soil Analysis. Chemical and Microbiological Properties*, edited by A. L. Page, R. H. Miller and D. R. Keeney, pp. 199-222. 2nd ed. vol. Agronomy Monograph No. 9, Part 2. American Society of Agronomy and Soil Science Society of America, Madison.

Nabhan, G. P.

1984 Soil Fertility Renewal and Water Harvesting in Sonoran Desert Agriculture: The Papago Example. *Arid Lands Newsletter* 20:21-28.

1979 The Ecology of Floodwater Farming in Arid Southwestern North America. *Agro-Ecosystems* 5:245-255.

1983 *Papago Fields: Arid Lands Ethnobotany and Agricultural Ecology*, The University of Arizona.

1986a 'Ak-cin 'Arroyo Mouth' and the Environmental Setting of the Papago Indian Fields in the Sonoran Desert. *Applied Geography* 6:61-75.

1986b Papago Indian Desert Agriculture and Water Control in the Sonoran Desert, 1697-1934. *Applied Geography* 6:43-59.

Niemeijer, D.

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

Norton, J. B.

1996 *Soil, Geomorphic, and Ecological Factors in Zuni Runoff Agriculture.* M.S., Iowa State University.

Norton, J. B., R. R. Pawluk and J. A. Sandor

1998 Observation and Experience Linking Science and Indigenous Knowledge at Zuni, New Mexico. *Journal of Arid Environments* 39:331-340.

Orr, B. R.

1987 *Water Resources of the Zuni Tribal Lands, McKinley and Cibola Counties, New Mexico.* U.S. Geological Survey Water-Supply Paper No. 2227. U.S. Geological Survey, Denver.

Papendick, R. I. and J. F. Parr

1992 Soil Quality: The Key to a Sustainable Agriculture. *American Journal of Alternative Agriculture* 7:2-3.

Parr, C. H.
1943 Flood Water Farming. *Indian Farming* 9(10):510-515.

Pawluk, R. R.
1995 *Indigenous Knowledge of Soils and Agriculture at Zuni Pueblo, New Mexico.* M. S. Thesis, Iowa State University.

Phillips, R. E., and D. Kirkham
1962a Mechanical Impedance and Corn Seedling Root Growth. *Soil Science Society of America Proceedings* 26(4):319-322.

1962b Soil Compaction in the Field and Corn Growth. *Agronomy Journal* 54: 29-34

Pierce, F. J. and W. E. Larson
1993 Developing Criteria to Evaluate Sustainable Land Management. In *Proceedings of the Eighth International Soil Management Workshop: Utilization of Soil Management Workshop: Utilization of Soil Survey Information for Sustainalbe Land Use, May 3, 1993.*, edited by J. M. Kimble, pp. 7-14. USDA Soil Conservation Service, Lincoln, Nebraska.

Sanders, W. T.
1992 Comments by William T. Sanders. In "Summary and Critique" by B.L. Turner II and W. T. Sanders. In *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica*, edited by T. W. Killion, pp. 263-284. The University of Alabama Press, Tuscaloosa.

Sandor, J. A.
1983 *Soils at Prehistoric Agricultural Terracing Sites in New Mexico.* Ph. D. Dissertation, Department of Soil Science, University of California, Berkeley.

Sandor, J. A. and N. S. Eash
1991 Significance of Ancient Agricultural Soils for Long-Term Agronomic Studies and Sustainable Agriculture Research. *Agronomy Journal* 83(1):29-37.

Sandor, J. A., P. L. Gersper and J. W. Hawley
1986 Soils and Prehistoric Agricultural Terracing Sites in New Mexico: I. Site Placement, Soil Morphology, and Classification: II. Organic Matter and Bulk Density Changes. Soils at Prehistoric Agricultural Terracing Sites in New Mexico: III. Phosphorus, Selected Micronutrients, and pH. *Soil Science Society of America Journal* 50:173-180.

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

Soane, B. D.
1982 Soil Degradation Attributable to Compaction Under Wheels and Its Control. *Soil Degradation.* Edited by D. Boels, D. B. Davies, and A. E. Johnston, pp. 27-45. Proceedings of the Land Use Seminar on Soil Degradation / 13-15 October 1980. A. A. Balkema, Rotterdam.

Soil Survey Staff
1993 *Soil Survey Manual.* 2nd ed Agricultural Handbook No. 18. U. S. Department of Agriculture, United States Government Printing Office, Washington, D.C.

1998 *Keys to Soil Taxonomy.* 8th ed. U. S. Department of Agriculture, Natural Resources Conservation Service, Washington, D. C.

1999 *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys.* 2nd ed. U. S. Government Printing Office, Washington.

Sojka, R. E. and D. R. Upchurch
1999 Reservations Regarding the Soil Quality Concept. *Soil Science Society of America Journal* 63(5):1039-1054.

Stevenson, F. J.
1982 *Nitrogen in Agricultural Soils.* Agronomy Monograph No. 22 ed. American Society of Agronomy, Madison.

Tisdale, S. L., W. L. Nelson, J. D. Beaton, and J. L. Havlin
1993 Soil Fertility and Fertilizers. 5th ed. MacMillan Publishing Company, New York.

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CHAPTER 4
INFLUENCES AND INTERACTIONS AMONG SOILS, PLANTS, AND ANTS IN A SEMIARID LANDSCAPE

A Paper to be submitted to *Pedobiologia*

Jeffrey A. Homburg and Jonathan A. Sandor

ABSTRACT

The western harvester (*Pogonomyrmex occidentalis*) and other closely related harvester ants (*P. barbatus*, *P. maricopa*, *P. Oweeyi*, and *P. rugosus*) are widespread in grasslands, deserts, and woodlands of the western U. S. Field research was undertaken to study interactions between western harvesters, soils, and vegetation patterns in west-central New Mexico. This study emphasizes the influence of western harvesters on physical and chemical soil properties, pedogenesis, and soil productivity. Ant colony and vegetation associations were documented in contiguous uncultivated, fallow, and cultivated field plots on an alluvial fan on the Colorado Plateau. Analyses made at pedon and microscopic scales are related to the broader landscape through observations of 73 ant colonies and previous studies of the age of western harvester colonies.

Results indicate that ant-affected soils have elevated levels of organic C, N, and available and total P. The southeast quadrant of ant mounds, the zone where entryways are concentrated, have particularly high nutrient levels for plants. Soil micromorphological studies show that the walls of ant chambers and channels are coated with organic matter. Spatial analysis indicates that ant colonies are more widely spaced in uncultivated fields

dominated by sagebrush than in fallow and cultivated maize fields where their primary food source, grass seeds from weedy vegetation, is concentrated. The soil turnover rate was estimated at 590 m^2/ha/y in the cultivated field, due to the ant's energetic response to nest disturbance caused by plowing. This rate is nearly 17 times that of the uncultivated field. Using projections based on biological studies of western harvester colony life span and field data on the amount of land modified by active colonies, we project that the entire landscape would be modified by ant activity in 2500 years for the uncultivated field, 300 years for the fallow field, and 50 years for the cultivated field. All three clearing intervals are within the time frame of agricultural practices in the Zuni area. Western harvesters may have a negative effect on soil productivity for agriculture in the short term, but over time, their overall effect is positive. Harvesters improve soil productivity by enriching the soil with nutrients, aerating it with their burrowing activity, and increasing the hydraulic conductivity and water-holding capacity.

INTRODUCTION

Mark Twain observed that, "As a thinker and planner the ant is the equal of (anyone)." (Quotation displayed at Museum of Natural History, Smithsonian Institution). Their social behavior, industrious nature, diverse subsistence patterns, and complex codes of communication are topics that have generated considerable scientific interest. This study focuses on how one widespread ant species, the western harvester ant (*Pogonomyrmex occidentalis*), influences and interacts with different soils and vegetation. Western harvesters and other earth-dwelling ants have played a significant role in pedogenesis throughout much of the world (Thorp 1949; Lyford 1963; Salem, Zarif et al. 1968; Czervinski et al. 1971; Jakubczyk et al. 1972; Wali and Kannowski 1975; Wiken et al. 1976; Mandel and Sorenson 1982; Culver and Beattie 1983; Levan and Stone 1983; Lockaby and Adams 1985; Carlson and Whitford 1991; Green et al. 1998). Their principal role involves pedoturbation (or mixing) by translocating soil to the surface during mound construction (Mandel and Sorenson 1982). As ants build chambers and channels and incorporate organic matter into their nest, they have a profound effect in increasing soil fertility, porosity, water-holding capacity, and thermal and hydraulic conductivity (Petal 1978; Wheeler and Wheeler 1986; Green et al. 1998).

In a study of western harvesters in semiarid grasslands of south-central Colorado, Mandel and Sorenson (1982) found that western harvesters concentrate carbonate-rich gravel and sand on the surface but move little clay to the surface, unlike ants in humid climates. Fine gravel placed on the mound surface serves as a mulch to retain soil moisture and moderate temperature changes in the mound. Because of low precipitation in their study area, Mandel and Sorenson (1982) argued that the effect of western harvesters on soil properties persist long after colonies are abandoned. As new colonies are established through time, the effect of ant-affected, or formicarious, pedons can extend to entire landscapes (Green et al. 1998). Despite the strong influence of ants on soil development, research on this topic has been sporadic (Green et al. 1998), certainly much less than the attention devoted to termites (Adamson 1943; Hesse 1955; Maldague 1959; Lee and Wood 1971; Lobry de Brun and Conacher 1990; Robinson 1958; Watson 1962; Stoops 1964; Williams 1968; Pomeroy 1976; Wood and Sands 1978).

The present study focuses on five research questions: (1) What chemical and physical soil properties are influenced by harvester ants in a semiarid, uncultivated field dominated by sagebrush, and how do they affect soil fertility? (2) What micromorphological properties are associated with ant-affected soils? (3) How do colony spacing, mound and clearing properties, and vegetation associations vary between colonies in uncultivated, fallow, and cultivated fields? (4) How does the rate of soil turnover vary between colonies in uncultivated, fallow, and cultivated fields? (5) How long could it take for the entire landscape to become affected by ant activity? (6) How do soils, plants, and ant colonies influence one another, and what are some of the major interactions between them? This investigation differs from previous soil studies of western harvesters in a number of ways. For one, it focuses on comparisons of ant activity in different and long-term cultivation contexts and relates their effect from the pedon scale to the broader landscape. Secondly, it is the first to examine harvester nests using soil micromorphology; and finally, it is the first to use a quadrant sampling scheme to test for spatial differences within the ant mound.

Study Area

This study was undertaken on the Colorado Plateau as part of an agroecological study of Zuni farming practices. The Zuni are one of western Puebloan tribes, and their traditional homeland extends over a large part of eastern Arizona and western New Mexico (Ferguson and Hart 1985). The project area is in small alluvial fan in the Rio Pescado watershed of the eastern part of Zuni Indian Reservation, at an elevation of about 2000 m. The climate is semiarid, with annual precipitation averaging about 300 mm, a summer-dominant rainfall pattern, and a frost-free season that typically extends from late May or early June to late October. Fieldwork was conducted on an alluvial fan that lies in a canyon valley cut into Cretaceous sedimentary rocks consisting chiefly of sandstone, siltstone, mudstone, and shale. The alluvial fan containing the uncultivated (or pasture), fallow, and cultivated fields examined by this study is depicted in Figure 4.1 in a 1988 aerial photograph.

Soils on the fan are formed in stratified Quaternary alluvium, with textures dominated by sandy loams and loams at the surface that overlie highly variable sequences of loams, clay loams, sandy clay loams, and sandy loams. The vertical and lateral textural variability is due to natural stratification associated with depositional events of varying magnitude. Despite this natural variability, clay enrichment with depth is indicated throughout the fan by the presence of shallow argillic horizon development. Clay illuviation has had a significant effect on vegetation distributions across the landscape because of how it promotes runoff, impedes infiltration, and conserves plant available moisture in the rooting zone. Sagebrush commonly grows taller and thicker in soils with illuvial B horizons, especially where runoff water flows and is concentrated.

Because of different land management practices for the study area parcels, vegetation varies widely between the three adjacent field plots that we sampled. Big sagebrush (*Artemesia tridentata*) and various grasses are dominant in the uncultivated field. A variety of weedy grasses and forbs grow in the fallow field, and maize and bind weed are the dominant plants growing in the cultivated field. The cultivated field is the site of a maize productivity study being conducted as part of this NSF-funded project. Vegetation diversity is described in more detail in the discussion of plant and ant colony associations. The uncultivated field has

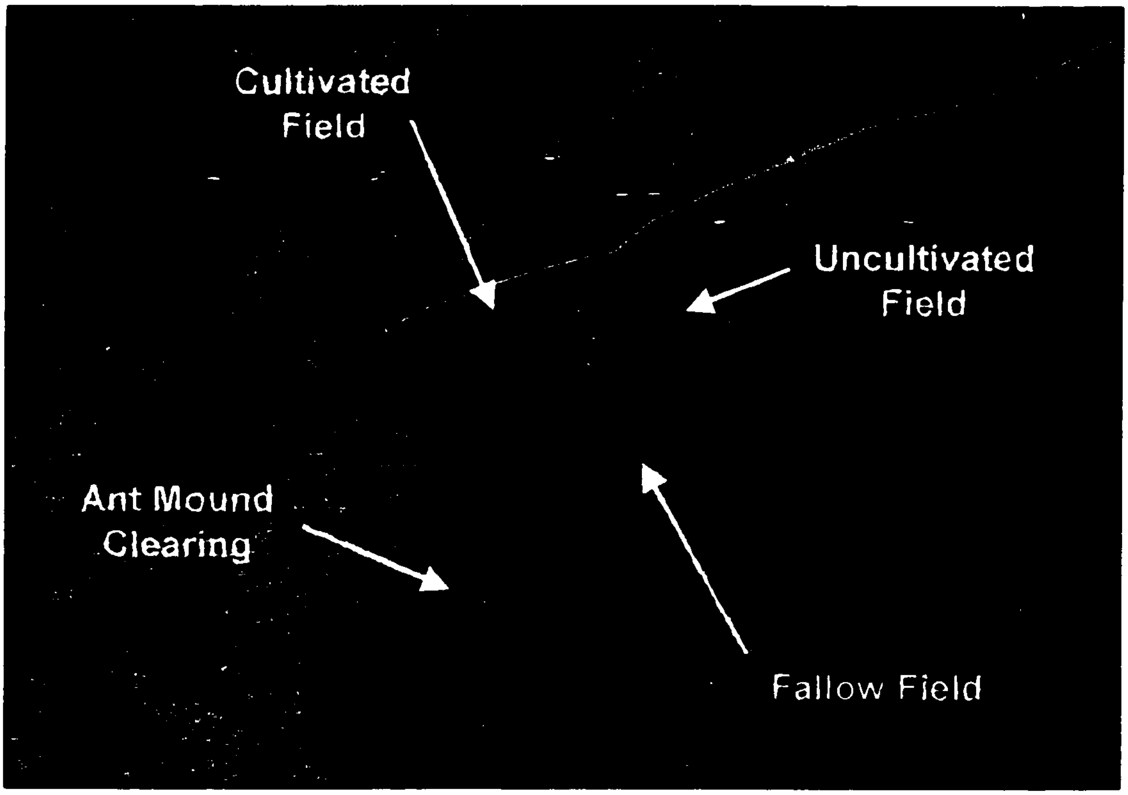

Figure 4.1. Aerial photograph of field plots. Fields are in the upper center, adjacent to the road. Note abundant small white dots, which are clearings around ant mounds.

been used as range land for cattle and sheep grazing for many decades, and the fallow land was last cultivated about 10 years ago. The rocky slopes and mesa tops around the alluvial fan are covered by a thick growth of juniper, pinyon and ponderosa pine (*Pinus edulis* and *ponderosa*), and Gambel's oak (*Quercus gambelii*), especially on the cool and moist north-facing slopes.

Background Discussion

Western harvester ants (also called the occident harvester or bearded ant) are mainly graniverous, but they are also scavenge and hunt other insects for food. *Pogonomyrmex* is known for seed-harvesting behavior but they are not the only harvester ants; other noteworthy myrmacine harvesters include *Veromessor* and *Aphaenogaster* in the American deserts, *Messor* and *Monorium* in the eastern hemisphere, and Pheidole from both the New and Old World (Dumpert 1981; Sudd and Franks 1987). Throughout the rest of this paper we use the term harvester in reference to the subgenus, *Pogonomyrmex*, and western harvester in reference to the species, *P. occidentalis*. *Pogonomyrmex* is the most distinctive of the American harvesters (Wheeler 1910).

In assessing why *Pogonomyrmex* store seeds, one study found that this strategy serves mainly to help withstand episodes of heavy predatory pressure, rather than to provide a ready food source for their brood, cope with unpredictable environments, or survive the winter (MacKay and MacKay 1984). Western harvesters prefer to build their nests in semiarid grasslands with sandy loam, clay loam, or loam soil textures, on gently sloping, south-facing terrain, but they have even been found on rocky, vertical cliffs (Gregg 1963; Moody 1982;

Taber 1998). Their colonies are concentrated between about 1400 and 2100 m in elevation, but colonies have been documented at elevations under 400 m and over 2700 m (Gregg 1963; Taber 1998; Wheeler 1963; Young 1964).

Western harvesters have dark red to dark reddish brown bodies that range from about 5 to 7 mm in length (Byars 1930; Wheeler and Wheeler 1986). Depending on the age of the colony, the population of workers in a colony ranges from about 400 to 9000 (Lavigne 1969). About 80 to 90% of the workers are confined to the nest, where they tend to the queen and her brood, build new chambers and tunnels, and husk seeds and dispose of the chaff. Only older workers, the most expendable of the colony, venture out of the nest to collect food, where they are vulnerable to predation by lizards, birds, spiders, and ant lions. Some predators are heavily dependent on harvesters for food. For example, harvesters account for up to 90% of the regale horned lizard's (*Phrynosomoa solare*) (Arizona-Sonoran Desert Museum 1998) diet and the Texas horned lizard (P. cornutum) feeds almost exclusively on harvesters (Whitford and Bryant 1979), and the ant's venom has little effect on both species.

Harvester ants also play an important role in human societies. Human consumption of large quantities of *Pogonomyrmex* venom has been documented in southern and central California, where American Indian groups use them ritually and therapeutically. Harvester ants are ingested to induce catatonic states and hallucinogenic visions, and to serve as curative and preventative medicine (Blackburn 1976; Groark 1996). Western harvester ants figure prominently in Zuni culture (Bunzel 1932; Tedlock 1979; Stevenson 1904) and other Puebloan tribes such as the Acoma (Taber 1988). Zuni pueblo is called Halona, which means Middle Ant Hill, and one Zuni religious society is known as the halo·kʷe (Red Ant People).

A 15-year study of colony dynamics in western Nebraska found that mean life expectancy for a colony of western harvesters was 43.5 years, which corresponds to the age of the queen (Keeler 1993). Unlike many other ant species, no multi-queen colonies of western harvesters have been observed (Cole and Wiernasz 2000). New colonies have higher death rates than established ones, but those that survive their first year have a life expectancy over a decade (Keeler 1993). Research on other harvester species indicates that colonies are more short-lived than those of the western harvesters, generally about 15 to 20 years (Porter and Jorgensen 1988; Gordon 1991).

Mounds serve as both incubators for their brood and defensible positions, and they also provide protection during floods. Mature mounds of western harvesters are conoidal in shape, and they average about 1 m in diameter and 35 cm in height (Scott 1951; Figure 4.2). The largest mound documented to date is about 1 m in height and 5 m in width (Schmidt et al. 1986). Most entryways are south- to east-facing to take advantage of solar warming in the morning (Wheeler 1910). They build the largest and most complex mounds of all harvesters, with nests up to 6 m deep (Gilbert 1960; Taber 1998). As is typical of other ants in dry climates, their nests are much deeper than those of ants in moist climates (Sudd and Franks 1987).

Mound size generally corresponds to age of the colony, except in cases when western harvesters move into abandoned nests (Keeler 1993). Mounds are interstratified and covered with mulch of fine gravel, granules, plant material, and other debris (e.g., charcoal, volcanic ash, gold dust, fossils, and cultural materials such as nails and fragments of glass) (Mandel and Sorenson 1982; Taber 1998). Western harvesters substitute gravel using other materials

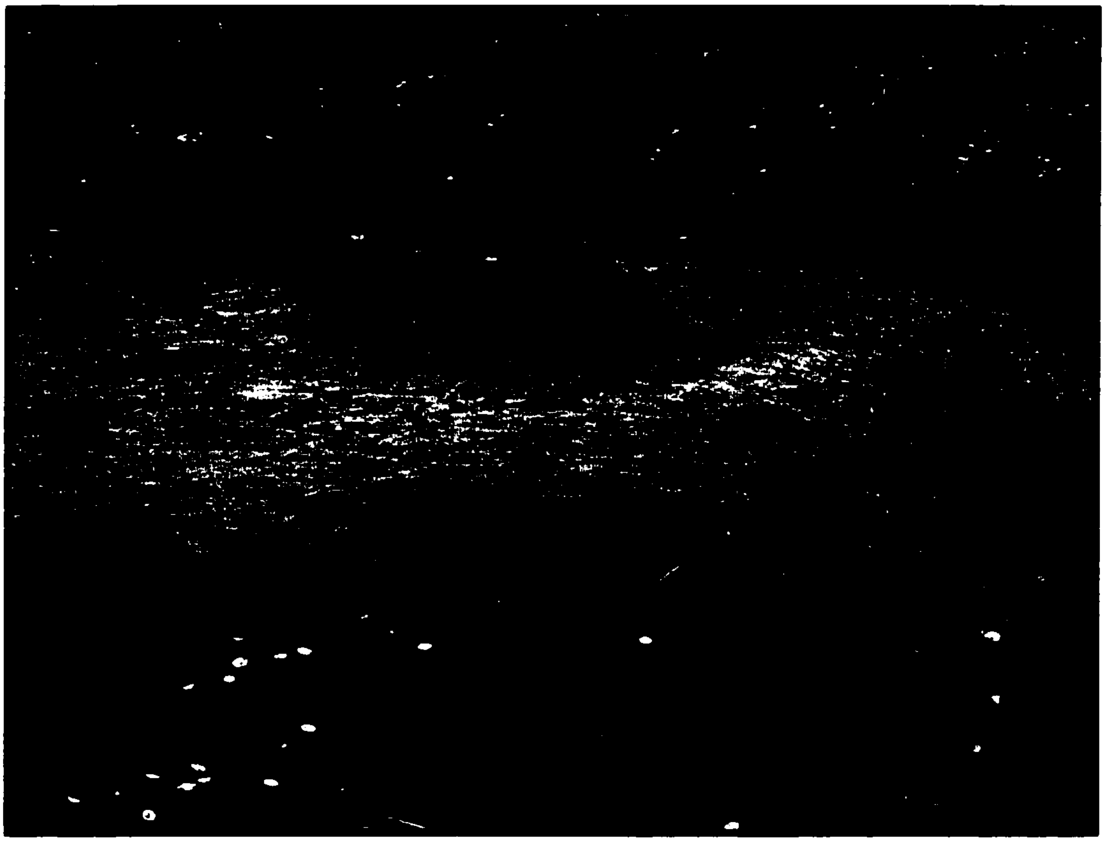

Figure 4.2. Typical ant mound and vegetation clearing of the western harvester ant.

(e.g., gypsum, lignite, petrified wood, empty snail shells, plant debris, granules of soil, etc.) when none is available (McCook 1882; Wheeler and Wheeler 1963). Prospectors and archaeologists use ant mound coverings to obtain clues as to what is buried below surface. Mulching material on the mound is bonded with oral secretions that act as "waterproofing" to promote water runoff from the mound (Taber 1998). When damaged by storms or animals, workers will repair the mound before seeking food (Taylor 1978). Other earth-moving activities besides mound construction include boring holes to the surface to dry the nest after heavy rains and plugging entryways with soil at sunset, the onset of winter, and during droughts, storms, and the threat of predators (McCook 1882; Taber 1998).

Harvesters expend substantial energy excavating and transporting soil material. They can carry a load 6 to 10 times their own weight (McCook 1882). The amount of soil moved by harvesters and other mound-building ants of the western U.S. is substantial, second only to that of humans (Scott 1951). Ants move more soil than earthworms, and in the process circulate vast quantities of nutrients vital to the health of land ecosystems (Hölldobler and Wilson 1994). Under shinnery oak (*Quercus harvardii*) and mesquite (*Prosopis glandulosa*) vegetation in southern New Mexico, western harvester ants moved about 80 g/m^2 of sandy loam soil to the surface in a single growing season (Whitford et al. 1986), which is about 100 times the rate noted in a mesic pasture in Colorado (Rogers 1972; Rogers 1974). Harvester ants are well adapted to excavate and transport dry sand, granules, gravel, and seeds. They have a psammophore (also called ammochaetae or beard) attached to their mandibles, and it is well developed in comparison to the closely related subgenus, *Ephebomyrmex* (Wheeler 1902; Cole 1968). The psammophore permits harvesters to carry a load four times heavier than that possible by the mandibles alone (Spangler and Rettenmeyer 1966). Mandibles and front feet are used to loosen the soil, and sandy soil is then packed with oral secretions in the psammophore to form a pellet as large or larger than their head (Wheeler and Wheeler 1963; Taber 1998). To our knowledge, the chemical content of their oral secretions has not been analyzed. Harvesters can also loosen dry soil by stridulation, a vibratory technique analogous to jackhammering (Stoops 1964). Stridulation is also used as a means of communication between ants. Based on alternating patterns of intensity, three different signals have been distinguished (Spangler 1967; Spangler 1973). Development of a beard and the ability to stidulate are clear indications of how soils have influenced harvester ant's anatomy and behavior.

Western harvesters build a system of multi-storied chambers and channels and they stabilize the walls by plastering them with oral secretions (Taber, 1998). Up to 150 chambers have been documented in a single nest, and different chambers serve as nurseries, granaries, and refuse disposal loci (McCook 1882; Taber 1998). Workers sort the brood into at least three groups (eggs and newly hatched larvae, growing larvae, and pupating larvae and pupae) that are moved between chambers to obtain optimal temperature and humidity conditions for incubation (Sudd and Franks 1987). Seeds are stored in the driest parts of the nest, and seeds that germinate are discarded from the nest. Refuse chambers that are filled are sealed from the rest of the nest (Hutchins 1967; Taber 1998). Some harvesters clear refuse from chambers in the spring and place it next to clearings around the mound (Gentry and Stiritz 1972). As they extend the size of their nest, infilled chambers and channels are favored excavation loci because of the ease of digging. The lowest chambers are used as overwintering facilities.

Western harvesters clear the vegetation bit by bit from several meters around their mound and place it outside of the denuded disk (see Figure 4.2). Techniques used for removing vegetation involve grasping plant debris with their mandibles, twisting it, and repeatedly pinching it until it is detached (Wu 1990). Debris is usually reduced to pieces that can be transported by one to three workers. Many explanations have been offered as the function of the clearing (Taber 1998), including: (1) protection of the mound from grass fires (Cole 1932); (2) making sunlight more effective in the morning (Wheeler and Wheeler 1986); (3) providing a target for males during their nuptial flight; (4) preventing roots from penetrating into their channels and chambers (Wu 1990); (5) removing competition with plants for moisture (Wight and Nichols 1966); (6) providing a surface for drying seeds and their brood; (7) dehumidifying and warming the underlying soil of the nest; (8) removing hiding places that could be used by predators; and (9) providing a surface for efficient travel by foragers. To this list, I add another possible function, one that involves water-harvesting. I noted a number of water puddles in the lowest part of the clearing, where a deflated desert crust forms a few centimeters below the surrounding terrain, so it is plausible that the clearing serves an important role in collecting water for use by the ants. It seems that the clearing serves a variety of purposes, and the mix and utility of functions probably varies seasonally and between different habitats.

Unlike many other ant species, there is no evidence that western harvesters secrete substances to recruit other ants to food sources (Cole 1968; Taber 1998). Instead of following scent trails, harvesters seek food by sight and use landmarks to navigate in their foraging area (Hutchins 1967). They do rely on chemical scents to recognize their nest mates, and chemicals incorporated in their nest permit them to distinguish their own nest from soil that is otherwise identical (Dumpert 1981). Florida harvesters secrete substances in their mandible gland that attract their nest mates at low concentrations and trigger aggression at higher quantities (Wilson 1958), so it is possible that western harvesters use a similar means of communication. Harvesters even communicate at death by releasing chemicals that signal workers to dispose of their bodies.

Ants form a variety of interactions with plants, not all of which are mutually beneficial (Huxley and Cutler 1991; Jolivet 1996). Because of their vegetation-clearing and seed-collecting behavior, many ranchers and farmers view harvesters as pests (Young and Howell 1964; Hutchins 1967; Wheeler and Wheeler 1986). The amount of denuded arable land is small, however, usually less than 2%, so they may cause only a minor decrease in agricultural yields. The long-term effect of western harvesters on rangeland may be more substantial, as they tend to reduce cover and species richness and diversity adjacent to the denuded clearing, and results of this influence linger long after colony are abandoned (Carlson and Whitford 1991). Even so, studies have found that western harvester queens prefer to establish nests on the bare ground of overgrazed rangeland, so it is unlikely they are a significant factor in rangeland degradation (Sharp and Barr 1960; Nagel and Rettenmeyer 1973). Furthermore, harvesters generally collect no more than about 5% of the grass seeds available, which is much less than that harvested by birds, mice, and other animals.

MATERIALS AND METHODS

Fieldwork was conducted in July of 1996 and 1998. Field observations were made for all active and abandoned ant colonies in three adjacent field plots, including a 0.87-ha uncultivated field, a 0.81-ha fallow field, and a 0.20-ha cultivated field. Observations made at each colony included measurements of the size of ant mounds and clearings, the number and location of nest entryways, and the spacing between adjacent mounds. Mound volumes were estimated by assuming a conical shape, using the formula: $V = \pi r^2 h/3$; where V = mound volume, π• = pi (or ca. 3.14), r = round radius, and h = mound height. The mounds are actually somewhat irregular cones (or conoidal), so the assumption of a cone for estimating the volume is a reasonable approximation. Colony spacing was determined by measuring the distance from the top of each mound to its nearest neighboring mound.

One very recently abandoned ant nest was selected for detailed soil analysis, for comparison with nearby uncultivated and fallow soils. Its recent abandonment was indicated by the conoidal shape and absence of vegetation on the mound, which contrasted with the dome-shape and small sagebrush associated with older, more eroded mounds. A 1 m by 2 m pit was excavated across the mound and surrounding clearing to document the nest architecture and soil profile. The soil profile was described, sampled, photographed, and drawn. Soil profile descriptions involved identifying soil horizons and recording morphological properties (e.g., depth, color, texture, structure, consistence, etc.) in accordance with procedures of the soil survey manual (Soil Survey Staff 1993). Pedons were classified using the most recent taxonomic keys (Soil Survey Staff 1998, 1999). Soil textures in the pedon descriptions (Appendix A) are field estimates, and this property was later measured in the lab.

In all, 47 bulk soil samples were collected and analyzed, including ten samples from the mound fill and submound profile, eight from the profile in the clearing around the mound, nine samples from a profile of the nearby fallow field, eight from a profile in the uncultivated field, five from different mound sectors (NE, NW, SW, and SE quadrants, and middle), and seven miscellaneous samples. The latter includes samples from a nursery area immediately below the mound, gravelly sediments from the mound surface and eroded from the mound, and granules from smal' active and abandoned ant mounds and areas neighboring each. These small (approximately 5-cm diameter) mounds are from another ant species, *Dorymyrmex pyramicus*, observed on many of the western harvester mounds and clearings, as others have reported (Wheeler 1910; Hutchins 1967; Wheeler and Wheeler 1973).

Seven soil samples were collected for micromorphological analysis under a petrographic microscope. These were collected from the mound, clearing around the mound, A horizon under the mound, and from open and filled ant chambers. To maintain the natural arrangement of peds and pores, the micromorphology samples were carefully pedastalled, removed, packaged, and transported to the lab. Samples were air-dried, impregnated with epoxy, and thin sections of about 30 micrometers in thickness were cut and mounted on slides by Spectrum Petrographics. Analysis focused on scanning slides to search for soil features and other attributes associated with ant activity.

Soil analyses focused on soil properties that are useful long-term measures of soil fertility. Particle-size and bulk density analyses were conducted to obtain data on soil texture and compaction. Chemical analyses included determinations of pH, organic carbon, nitrogen, and total and available phosphorus. Particle-size, bulk density, and pH analyses were completed in soil labs at Iowa State University, and organic carbon, total nitrogen, and total and available phosphorus analyses were conducted at the University of Montana. Initial sample preparation involved air-drying and sifting samples through a 2-mm sieve to remove gravel, roots, and other coarse undecomposed organic debris. Determinations of organic carbon, nitrogen, and total phosphorus analyses were done on ten-gram samples that were mechanically ground fine enough to pass through a No. 100 sieve.

Particle-size distributions were determined using the sieve and pipette method (Gee and Bauder 1986: Method 5.4), with samples pretreated with a 30 percent hydrogen peroxide reagent for organic matter digestion and a sodium hexametaphosphate solution for clay dispersion. Bulk density analysis was measured using the clod method, using paraffin-coated peds (Blake and Hartge 1986: Method 13.4). Bulk density samples were analyzed in duplicate and averaged, and if the coefficient of variation exceeded 5%, a third sample was analyzed and average with the others. After peds were weighed in water, gravel was removed and weighed, so the bulk density of the <2 mm fraction could be determined. Soil pH was measured electrometrically in the lab using a 1:1 suspension (weight basis) of soil and distilled water using a glass electrode (McLean 1982). Soil pH was also estimated by colorimetry in the field and these results are included in the pedon descriptions (Appendix A). Total carbon and nitrogen concentrations were determined using a Leco CHN analyzer, and inorganic carbon was measured by titrimetry (National Soil Survey Center 1996). Total carbon was assumed to represent the organic carbon level due to lack or near absence of carbonates in all samples. Total phosphorus concentrations were determined using an alkaline oxidation extract (Dick and Tabatabai 1977), and available phosphorus was measured using the Olsen extraction method (Olsen 1982: Method 24-5.5.2).

RESULTS AND DISCUSSION

Soil Morphology and Ant Nest Relationships

Soil profile descriptions from the formicarious pedons and fallow and uncultivated soils are presented in Appendix A, and the color, texture, and structure of the main soil horizons are summarized in Table 4.1. Both formicarious pedons are classified as Fine-loamy, mixed, mesic Aridic Haplustalfs at the family level, and the fallow and uncultivated pedons are both classified as Fine-loamy, mixed, mesic, Aridic Argiustolls in the other two pedons. Morphological differences in the control section are not great between the two families. The Aridic Argiustolls only have a slightly darker color, enough to meet the minimal requirement for a mollic epipedon.

Pedons in both families have shallow argillic horizons. It is noteworthy that buried argillic horizons were also found in the profile of all pedons examined. The shallow and multi-storied argillic horizons strongly influence pedogenic development, and ant nests were probably built in a way to take advantage of their physical effect in impeding infiltration and enhancing water retention, even though argillic development is not strong in the field studied. Ant chambers are concentrated in the upper 40 cm, which is coincident with the greatest argillic horizon development. The most important morphological differences between formicarious and fallow or cultivated soils are ones that are rather obvious, but they are worth reviewing nevertheless. Formicarious pedons are riddled with network of horizontal,

Table 4.1. Color, texture, and structure of principal soil horizons.

Pedons	Horizon (1)	Dry Color	Dominant Texture	Structure (2)
Mound/submound	mound fill	brown	gravelly sandy loam	moderate platy and weak to moderate granular
	A	brown	fine sandy loam	weak to moderate granular and moderate sbk
	Bt	brown	loam to sandy clay loam	moderate to strong sbk
	Btk	brown to pale brown	sandy loam to loamy sand	weak to moderate sbk
	BCtk	brown	sandy loam	weak to moderate sbk
Clearing	A	pale brown	fine sandy loam	moderate platy and weak to moderate granular
	Bt	brown	loam to sandy clay loam	moderate to strong sbk
	Btk	brown	sandy loam	weak to moderate sbk
	BCtk	brown	sandy loam	weak to moderate sbk
Fallow	Ap	brown	sandy loam	weak platy and granular, and weak to moderate sbk
	Bt	brown	clay loam	weak to moderate sbk
	Bt or BCt	yellowish brown	sandy loam to sandy clay loam	weak sbk
	2Btk	yellowish brown	clay loam	moderate sbk
Uncultivated	A	brown	loam	weak platy and weak to moderate granular
	Bt	brown	loam to sandy clay loam	moderate prismatic and weak sbk
	BCt	brown to yellowish brown	loamy sand to loam	massive

1 - does not include all transitional horizons and data for subhorizons are combined as one horizon.

2 - sbk = subangular blocky; all plates are thin, granules are fine, and subangular blocks are medium or coarse

chambers connected by near- vertical tunnels (Figures 4.3-4.4). Chambers are commonly 15 cm wide and 2 cm tall, and the channels are about 1 cm wide. Such large, interconnected pores are significant pedogenically. Unlike planar pores between peds that may swell shut when wet, ant chambers and channels tend to remain open, and they persist for some time after nest abandonment so they continue to serve as air and water conduits. Decomposed organic matter coats the walls of chambers and channels, as shown in Figure 4.5a. These coatings commonly have successive layers of organic matter deposition. Similar organic-rich colloidal infillings were identified in thin sections of nest walls of *Lasius neoniger* (Wang et al. 1995).

Textural sequences with depth vary considerably between pedons, due largely to depositional variability in different parts of the alluvial fan. Sandy loams, sandy clay loams, and clay loams are dominant in all pedons, and coarser textured topsoils overlie zones of clay-enrichment in the argillic horizon. The gravelly nature of the mound fill, especially in the upper fill deposit, is a distinctive attribute of soil redistribution by ants. Fine gravel content is typically two to five times higher in the mound fill than that of the submound soil. The gravelly mound surface and fill is effective at maintaining dry conditions in the mound by slowing capillary rise of soil moisture and helping to shed runoff. When we first exposed the mound in cross section, a zone of wetting was apparent, and it was thicker in an apron around the mound. Many chambers were found along a diagonal line immediately below this moist soil. In addition to gravel, small quantities of seed chaff and insect remains were encountered in the mound fill (see Figure 4.5b).

Soil color is relatively homogeneous in both the mound fill and submound soils, so

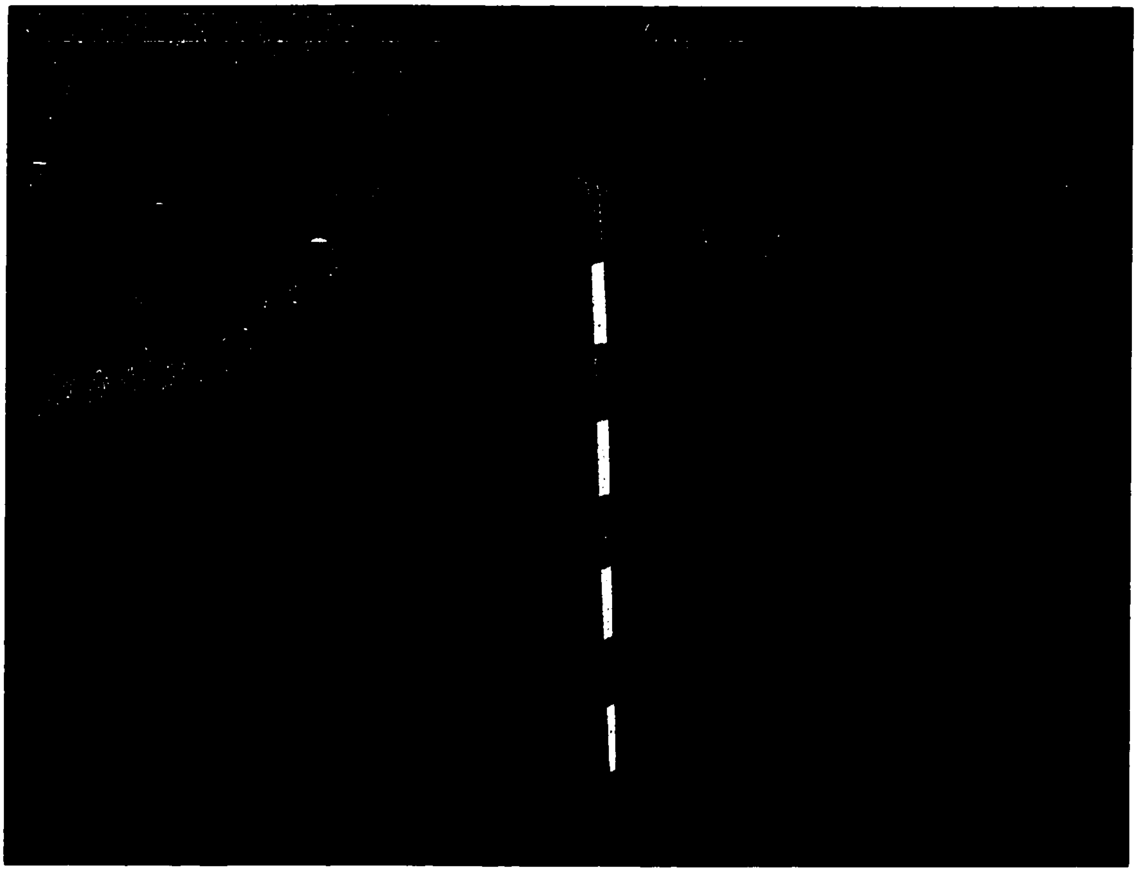

Figure 4.3. Ant mound in profile.

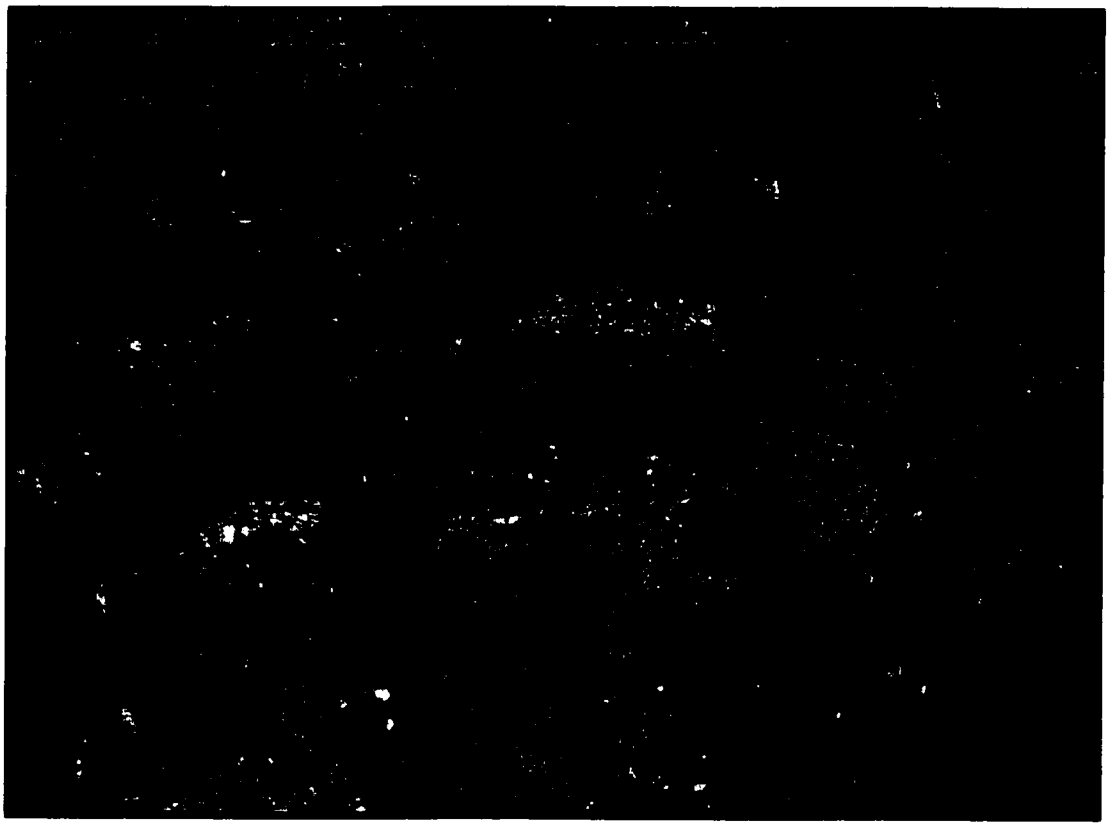

Figure 4.4. Ant chambers in cross section.

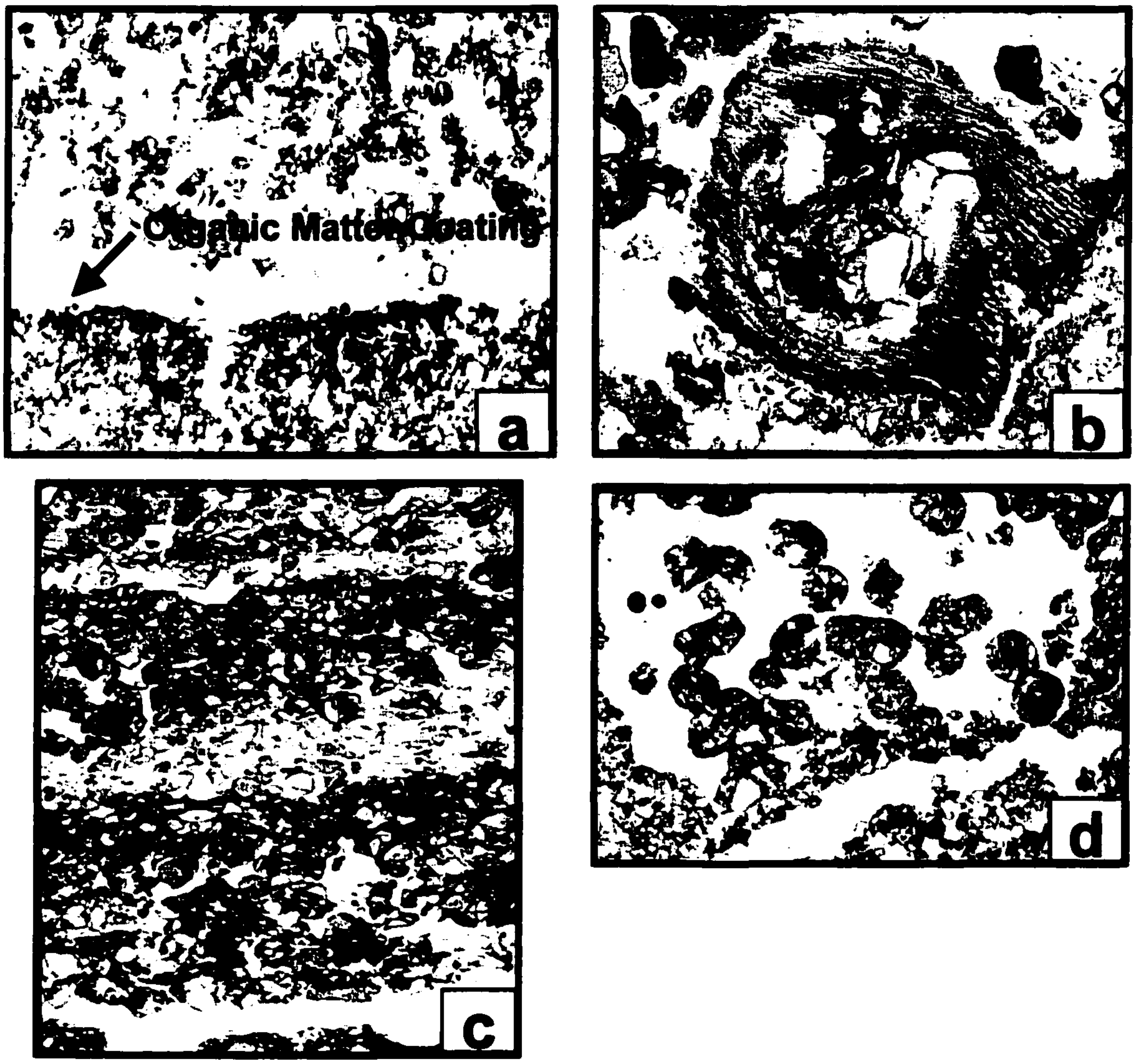

Figure 4.5. Photomicrographs of: (a) ant chamber wall coated with organic matter, frame length = 7 mm; (b) chaff from brome seed incorporated in ant mound, frame length = 3.5 mm; (c) platy structure of surface of clearing around mound, frame length = 3.5 mm; and (d) chamber of undetermined species containing fecal material, adjacent to ant chamber, frame length = 1.75 mm.

this property does not help in estimating the relative contribution of different soil horizons to the concentrations vary incrementally and cumulatively with depth. Contrasting soil colors have been used for such an objective in studies of western harvesters in Colorado (Mandel and Sorenson 1982) and common eastern mound-building ants (*Formica exsectoides*) in Wisconsin (Salem, 1968). In this study the cross-sectional area indicated that about 90% of the mound fill is derived from the upper 40 cm.

The topsoil of the clearing is pale brown (dry), which is lighter than the A horizons of other pedons (see pedon descriptions in Appendix A). This change in a soil property is due mainly to its lower organic matter content. Platy structure is more strongly developed at the surface of the clearing than elsewhere, probably caused by more frequent wetting and drying cycles (see Figure 4.5c). This difference shows that desert crusts are better developed in clearings. Such crusting indicates that water infiltration is slowed in the clearing, and this interpretation is consistent with observations that puddles remain in the lowest part of clearings after runoff events.

Ant Influences on Physical and Chemical Soil Properties

Soil chemistry, bulk density, and particle-size data for the profiles, mound, and other samples are presented in Tables 4.2 and 4.3. Table 4.4 shows soil data comparing different mound sectors with pedons from the clearing, and uncultivated and fallow field, adjusted to account for bulk density differences. Values in Table 4.4 represent a weighted mean adjusted for soil horizon thicknesses in the upper 1 m, the zone encompassing most of the ant nest.

Table 4.2. Soil data for pedons.

Sample	Depth (cm)	pH	Org C (g/kg)	N	C:N	Av. P (mg/kg)	Total P	BD (g/cm3)	vcs	cs	ms	fs	vfs	S	Csi	Fsi	Si	C
Ant Nest																		
Mound Mound	20-18	6.0	12.5	1.04	12.0	29.9	373	1.40	11	3	9	20	18	60	17	13	30	10
Mound fill	18-10	6.7	13.8	1.00	13.7	34.9	329	1.43	8	2	10	22	18	59	16	13	29	12
Mound fill	10-0	6.1	12.6	0.96	13.2	21.5	316	1.30	10	3	9	19	18	59	16	13	29	12
A	0-10	7.0	6.9	0.56	12.4	8.3	256	1.45	2	2	11	26	19	59	14	13	27	14
Bt1	10-20	7.2	8.0	0.64	12.5	2.0	193	1.58	0	1	6	22	24	52	16	11	27	21
Bt2	20-35	7.5	9.5	0.67	14.1	1.7	173	1.46	1	2	8	16	17	44	16	17	33	23
Btk1	35-57	7.8	8.9	0.65	13.7	2.3	197	1.57	0	2	8	20	17	46	15	14	30	25
Btk2	57-72	6.0	8.5	0.44	19.5	3.2	177	1.50	1	4	15	25	16	61	10	10	20	18
BCtk	72-106	8.2	7.1	0.37	19.4	3.9	135	1.41	1	2	10	32	22	66	9	9	18	16
2BCtk	106-124	8.3	5.9	0.36	16.6	3.2	162	1.38	3	7	18	19	18	65	12	9	20	15
Clearing																		
A1	0-3	6.1	6.1	0.44	14.0	17.2	258	1.49	10	2	10	24	21	66	19	8	28	6
A2	3-11	6.1	7.0	0.50	13.8	23.8	278	1.60	3	2	11	23	18	57	16	12	28	15
ABt	11-18	6.7	7.3	0.63	11.6	13.8	228	1.47	0	2	10	23	20	54	16	11	27	19
BAt	18-25	7.0	8.9	0.66	13.4	2.9	250	1.57	1	1	6	15	16	38	20	17	37	25
Bt1	25-59	7.3	7.2	0.53	13.7	3.0	189	1.52	1	2	9	20	19	51	16	11	27	22
Bt2	59-68	8.0	5.9	0.30	19.3	3.1	220	1.43	1	7	20	26	13	67	7	10	17	17
Btk	68-96	8.2	6.0	0.36	16.4	3.5	146	1.43	1	3	14	29	19	67	9	9	18	15
BCtk	96-124	8.3	3.4	0.20	17.0	3.9	126	1.38	3	4	18	33	19	76	7	6	13	11
Fallow Field																		
Ap	0-17	6.8	8.7	0.76	11.5	8.7	237	1.45	1	3	12	35	16	67	9	10	19	12
ABt	17-28	6.6	6.1	0.61	10.0	6.1	216	1.55	1	2	11	36	17	67	19	14	34	12
Bt	28-40	6.7	6.7	0.63	10.7	6.7	263	1.50	2	3	10	32	14	61	13	9	22	17
Bt	40-68	6.8	5.8	0.54	10.7	5.8	223	1.46	1	2	9	34	15	60	15	11	26	16
Bt or BCt	68-81	7.0	3.8	0.37	10.3	3.8	194	1.46	2	3	12	37	16	69	12	9	22	12
Bt or BCt	81-105	7.6	6.5	0.48	13.4	6.5	206	1.40	1	1	5	31	20	57	11	15	26	18
2Btk1	105-141	7.8	8.7	0.59	14.9	8.7	247	1.54	0	1	6	17	9	34	9	23	33	33
2 or 3Btk2	141-150	7.8	6.0	0.40	15.0	6.0	191	1.46	1	3	14	35	15	68	10	9	19	13
Auger	270-300	7.8	6.9	0.34	20.1	6.9	204		1	1	6	25	25	57	12	13	25	18
Uncult. Field																		
A	0-9	6.4	22.7	1.63	14.0	22.7	412	1.48	0	3	11	21	12	46	14	23	37	16
BAt	9-27	6.6	11.2	0.73	15.3	11.2	268	1.50	1	2	11	25	14	52	16	16	33	16
Bt1	27-59	6.7	8.0	0.59	13.4	8.0	255	1.58	1	2	8	25	13	48	11	18	28	21
Bt2	59-82	6.7	5.9	0.49	11.9	5.9	227	1.63	0	1	4	25	19	50	13	14	26	24
BCt1	82-101	6.7	5.9	0.47	12.7	5.9	215	1.52	1	3	14	27	11	55	5	14	19	23
BCt2	101-132	7.0	5.8	0.44	13.1	5.8	224	1.46	1	1	7	27	19	55	12	12	24	21
BCt3	132-150	7.7	4.7	0.33	14.4	4.7	195	1.49	0	2	10	38	17	67	8	10	18	15
Auger	275-300	6.6	7.3	0.43	17.1	3.5	226		0	0	2	9	14	25	17	25	42	33

Note No bulk density determinations were made for augered samples.
vcs – very coarse sand; cs - coarse sand; ms - medium sand; fs - fine sand; vfs - very fine sand; S - sand
CSi - coarse silt; FSi - fine silt; Si - silt; C - clay.

Table 4.3. Soil data for mound sector and miscellaneous samples.

Sample	Depth	pH	Org C	N	C:N	Av. P	Tot. P	BD	vcs	cs	ms	fs	vfs	S	CSi	FSi	Si	C
	(cm)		(g/kg)			(mg/kg)		(g/cm3)										
Mound Sectors																		
NE 1/4	20-0	6.1	11.1	0.57	19.6	34.0	368	1.37	12	3	9	20	17	60	15	11	27	13
NW 1/4	20-0	6.5	12.6	0.62	20.4	18.0	320	1.36	11	3	10	21	18	62	16	12	28	11
SW 1/4	20-0	6.5	8.9	0.71	12.6	31.7	357	1.42	9	3	9	20	17	58	17	12	29	14
SE 1/4	20-0	6.0	9.9	1.08	9.2	114.8	768	1.65	9	2	8	19	18	57	17	12	29	14
Center	20-0	5.9	10.7	0.87	12.3	48.0	372	1.60	9	2	8	20	19	57	17	13	30	13
Misc. Samples																		
Mound center, nursery area	0-10	6.5	8.2	0.65	12.7	22.7	259	1.35	2	2	10	26	19	59	16	11	27	14
Gravelly sediment eroded from mound	0-1		7.8	0.70	11.1	14.5	394		30	5	13	22	13	82	7	5	11	7
Gravelly sediment from mound surface	0-1		8.3	0.65	12.8	21.3	424		18	3	7	16	16	60	19	13	32	8
Soil adjacent to small ant mounds	0-1	6.5	7.9	0.62	12.6	19.2	261	1.54	0	2	9	22	21	54	25	13	39	8
Soil adjacent to small ant mounds	1-5	6.5	7.4	0.57	13.0	14.9	316	1.56	1	2	11	24	19	57	17	16	33	10
Granules from small abandoned mounds	0-1	6.5	8.8	0.73	12.1	16.3	232		1	2	13	25	19	60	15	11	25	15
Granules from small active mounds	0-1	6.9	8.7	0.72	12.1	13.5	243		1	2	12	25	19	59	15	11	26	15

Note: Missing pH and bulk density data is for some gravelly sediment/granules.
vcs - very coarse sand; cs - coarse sand; ms - medium sand; fs - fine sand; vfs - very fine sand; S - sand
CSi - coarse silt; FSi - fine silt; Si - silt; C - clay.

Table 4.4. Comparison of pH, nutrient concentrations, and physical soil properties for mound and off-mound areas.

Sample	pH	C	N	Av P	P	C:N	Bulk Den.	Sand	Silt	Clay
		(kg/m3)	(kg/m3)	(kg/m3)	(kg/m3)	Ratio	(g/cm3)	(%)	(%)	(%)
Ant Mound, NE 1/4	6.1	15.2	0.78	0.047	0.50	19.6	1.37	60.0	26.7	13.4
NW 1/4	6.5	17.1	0.84	0.024	0.44	20.5	1.36	61.5	27.5	11.0
SW 1/4	6.5	12.6	1.00	0.045	0.51	12.6	1.42	57.5	28.8	13.7
SE 1/4	6.0	16.3	1.78	0.189	1.27	9.2	1.65	56.8	28.8	14.4
Center	5.9	17.1	1.39	0.077	0.60	12.3	1.60	57.4	29.6	13.0
Clearing Around Mound	7.5	10.0	0.69	0.009	0.29	14.4	1.49	57.9	23.8	18.3
Uncultivated Field	6.7	13.9	1.03	0.014	0.40	13.6	1.56	50.8	28.2	21.0
Fallow Field	6.9	9.2	0.82	0.009	0.33	11.2	1.46	61.5	24.1	14.5

Note: Values for clearing, uncultivated and fallow field represent a weighted mean by soil horizon to 1 m.

Differences between mound and off-mound soils are shown graphically in Figure 4.6, and stacked bar graphs in Figure 4.7 show how soil nutrient concentrations vary incrementally and cumulatively with depth. Soil data from previous soil studies of western harvester and *Formica* nests are summarized relative to reference samples in Table 4.5. Mound fill is slightly to moderately acid (pH 5.9-6.5), which is lower than the neutral reference soils from the uncultivated (pH 6.7) and fallow fields (pH 6.9) (see Table 4.3 and Figure 4.6). The A horizon of the clearing is also acidic, at pH 6.1, but the clearing pedon as generally slightly alkaline (pH 7.5), due to greater leaching from the surface and accumulation of carbonates below 68 cm depth. Most nutrients are readily available to plant roots in ant-affected soils at these pH values, and in fact, pH 6.5 is considered optimal for maize production. Optimal pH levels are between pH 6 and 8 for nitrogen availability (Foth and Ellis 1988) and between pH 6 and 6.5 for phosphorus uptake (Tisdale et al. 1985). Changes in soil pH in ant nests have been documented, and these changes are presumably due to changes in the amount of organic matter and exchangeable cations. Compared to soils away from ant nests, soil pH in ant-affected soils tends to increase in acid soils (Salem et al. 1968), decrease in alkaline soils (Mandel and Sorenson 1982), and only slightly decrease or increase in neutral soils (Petal 1978). Ants may be able to regulate soil pH in the nest, but the particular mechanism is unknown (Petal 1978).

Organic carbon concentrations (standardized on weight/volume basis) vary from 12.6 to 17.1 kg/m^3 in the mound fill, and these levels are significantly elevated above off-mound soils (see table 4.4 and Figure 4.6). As previously shown in Figure 4.5a, organic matter is strongly associated with nest chambers and tunnels. Fecal matter from smaller soil fauna

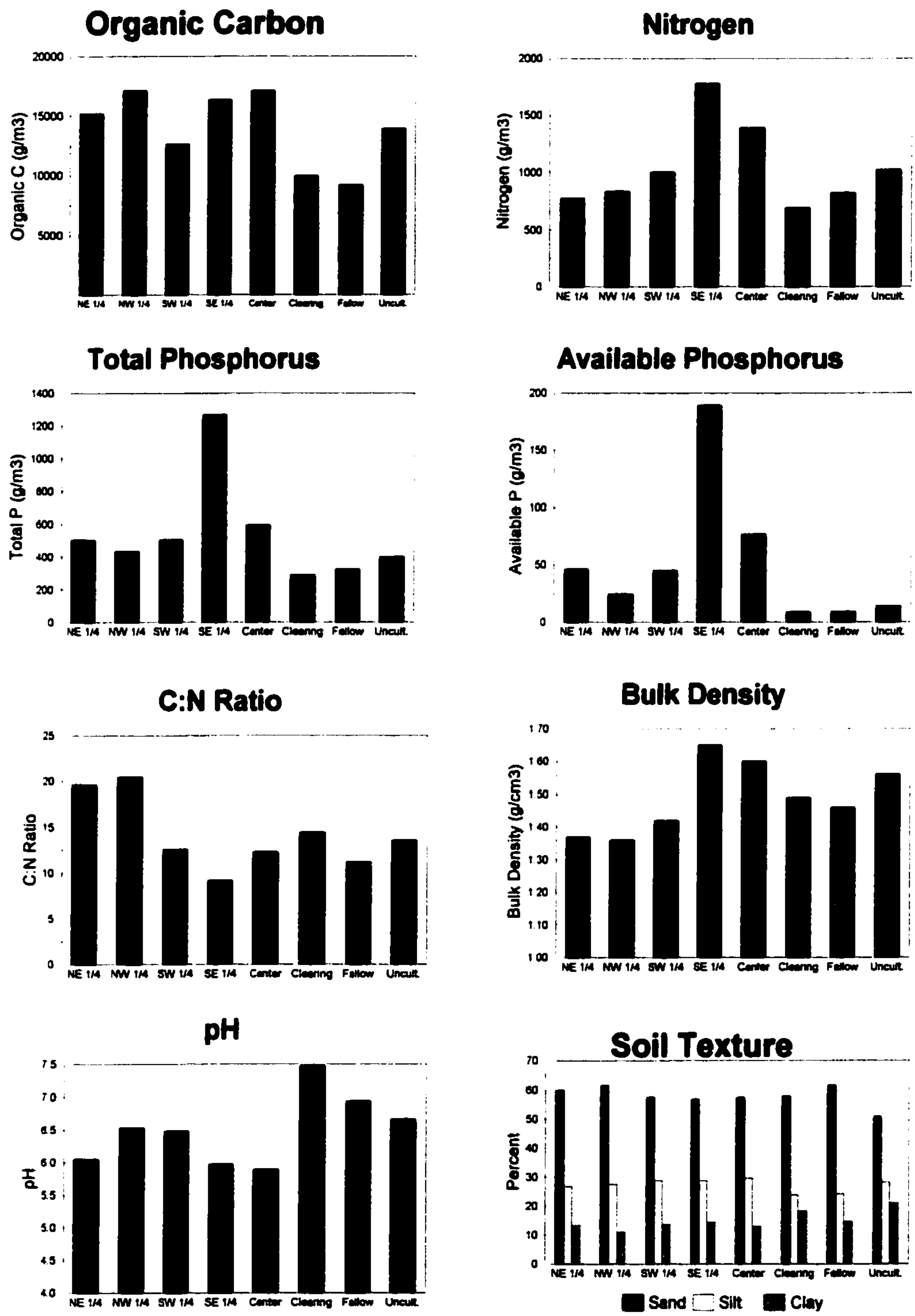

Figure 4.6. Histograms of soil data for mound and off-mound areas.

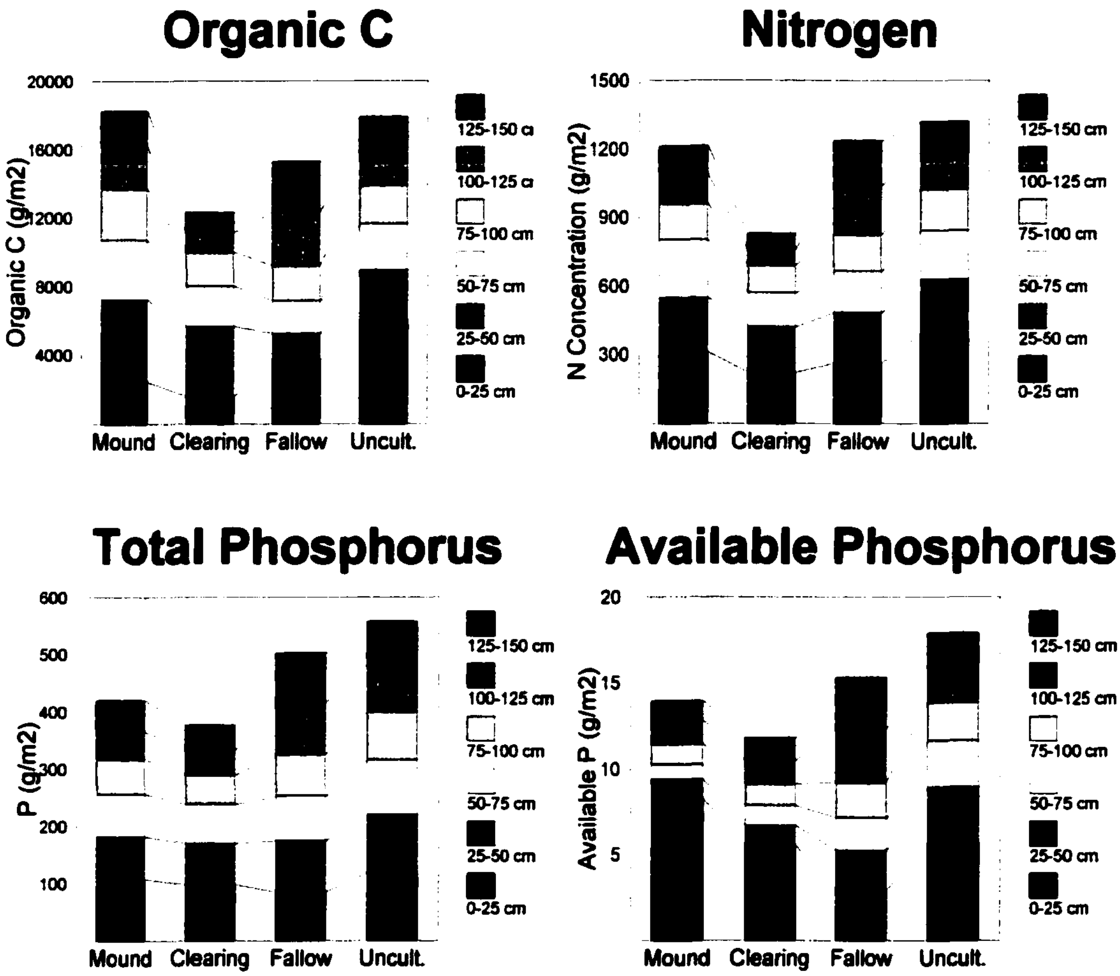

Figure 4.7. Bar graphs of organic carbon, nitrogen, and total and available phosphorus distributions with depth.

Table 4.5. Summary of studies that have compared ant mound and reference soils.

Sr. Author Ant Species, Project Area,	pH			Org. C (g/kg)			N (g/kg)			Av. P (mg/kg)			Bulk Den. (g/cm3)			Sand (%)			Silt (%)			Clay (%)		
	M	S	R	M	S	R	M	S	R	M	S	R	M	S	R	M	S	R	M	S	R	M	S	R
This study	6.2	7.3	6.6	10.6	8.4	12.7	0.8	0.6	0.9	49.3	3.5	12.7	1.4	1.5	1.5	59	50	49	28	30	32	13	20	18
P. occidentalis																								
New Mexico																								
Sage, grass																								
Mandel (1982)	8.1	8.4	8.3				1.6	0.8	0.6							77	46	44	15	32	33	8	22	24
P. occidentialis																								
Colorado																								
Grass, sage																								
Carlson (1991)	6.4		6.2	11.0		7.0				19.3		1.5	1.2		1.2	82		74	16		23	1		3
P. occidentalis	6.4		6.8	13.9		20.3				25.4		5.2	0.8		0.8	84		83	14		15	1		1
New Mexico																								
PJ, ponderosa																								
Wiken (1976)				20.0	9.4	7.3										36	44	42	35	34	36	30	22	22
Formica fusca																								
SW Canada																								
Fir, grass																								
Culver (1983)	5.5		5.4	25.0		32.5				11.7		8.4												
F. canadensis																								
Colorado																								
Grass																								
Salem (1968)	7.2	5.9	5.3	15.7	8.5	7.4							0.8	1.2	1.3	3	3	3	50	61	54	47	36	43
F. exsectoides																								
Wisconsin																								
Oak, Grass																								
Baxter (1967)	6.0	5.3	5.2	24.4	15.7	16.5				82	22.2	19.4	0.6	1.1	1.3							29	29	28
F. cinerea																								
Wisconsin																								
Grass																								

Note: Soil data for Carlson (1991) separate for pinyon-juniper (upper) and ponderosa pine (lower)
M = mound soil S = submound soil, R = reference soil.

living ant nests also contributes to organic matter additions (see Figure 5d). The total amount of organic carbon in the upper 1.5 m of the mound and submound soil is comparable to soils in the uncultivated field and higher than those of the clearing and fallow field (see Figure 4.7). Because semiarid soils are naturally low in organic matter content, due to aridity, low biomass production and rapid oxidation, any process than can increase it can be an important long-term benefit to plants.

Compared to off-mound samples, nitrogen levels are elevated in the southeast quadrant and center of the mound, where entryways and chambers are concentrated. Elsewhere in the mound nitrogen levels are similar to the reference samples. Other studies of western harvester mounds have found elevated levels of nitrogen (Mandel and Sorenson 1982), and both nitrate-N (NO_3-N) and ammonium-N (NH_4-N) (Carlson and Whitford 1991). Western harvesters increase nitrogen levels by depositing undecomposed and humified organic matter in the mound. Nitrogen is usually the most limiting nutrient for agricultural production in the semiarid Southwest, so any process that makes it available to plants roots is significant.

The southeast and center sectors of the mound also have low C:N ratios compared to other mound and off-mound areas. Low C:N ratios may indicate an advanced state of organic matter decomposition by microbial activity. As microbes convert organic carbon to gaseous carbon dioxide, carbon is released to the atmosphere, nitrogen is combined into new protein molecules, and the C:N ratio narrows through time. Alternatively, the ants may simply concentrate refuse and other debris with a naturally low C:N ratio in the mound.

Total and available phosphorus levels are higher in the mound soils than off-mound areas, especially in the southeast mound sector. Differences between mound and off-mound available phosphorus levels are greatest in the upper 25 cm, where plant roots are concentrated and can thus take advantage of its availability. This is noteworthy given that total and available phosphorus in upper 1.5 m is actually lower than that of the uncultivated and fallow fields (see Figure 4.7). Because phosphorus levels are slow to change in the soil, increases could have a long-lasting beneficial effect on agricultural production. Phosphorus requirements for crops are not well understood for Southwest soils, but available phosphorus levels below 2 mg/kg (or 2 ppm) are usually considered low and values above 5mg/kg are considered sufficient (Doerge 1985).

Bulk densities are 1.60 to 1.65 g/cm^3 in the center and southeast mound sectors, which is substantially higher than in the off-mound samples, which average about 1.5 g/cm^3. Other parts of the mound have much lower bulk densities, ranging from 1.36 to 1.42 g/cm^3, and these values are probably more representative of the mound as a whole. Although the mound that was sampled was recently abandoned, there has been considerable slaking and infilling of entryways and passageways in the southeast and center mound sectors. These processes appear to be responsible for significant compaction there. Overall, ant activity in this study area appears to have resulted in decreased bulk density. Both decreased (Rogers 1972) and increased (Carlson and Whitford 1991) bulk densities have been found in the western harvester mounds in other studies. Decreased bulk densities are associated with many properties beneficial to plant production, including improved air and water permeability, moisture retention, seedling emergence, and root penetration, and increased densities have the opposite effect.

On average, the mound fill had higher sand (59% vs. 40%) and lower clay (13% vs. 18%) contents compared to the upper 40 cm of the submound soil. As noted previously, fine gravel content is about two to five times higher in the mound than the submound. Similar trends were also found other studies of western harvester mounds (Mandel and Sorenson 1982; Carlson and Whitford 1991). Elevated sand and gravel contents promote aeration and rapid water infiltration into the rooting zone.

Except for clay and silt content, few differences were found between the abandoned and active mound soils of *Dorymyrmex pyramicus* and their reference samples. Their mounds have much higher clay contents and decreased silt contents compared to their reference soils, which is a major contrast with the results of the western harvester mound soil. *Dorymyrmex* mounds also have slightly elevated pH, organic carbon, and total phosphorus levels, but all other soil test values are very similar or even slightly decreased compared to their reference samples (see Table 4.3).

Surficial Ant Nest Morphology, Colony Spacing, and Vegetation Associations

In all, 73 ant colonies were documented in this field study, including 62 active and 11 abandoned mounds. Within the 1.88-ha area where mounds were examined, total mound fill was estimated at 2.74 m^3 for the active mounds and 0.22 m^3 for the abandoned mounds. Sixteen active and six abandoned colonies were found in the uncultivated field; 40 active and five abandoned colonies were noted in the fallow field, and six active colonies were observed in the cultivated field. All field observations of ant mounds, cleared areas, and vegetation associations are summarized in Tables 4.6 and 4.7.

Colony spacings have been studied using many techniques (Southwood 1973), but the most common method, and the one used by this study, is nearest neighbor analysis (Clark and Evans 1954). Nearest neighbor analysis shows that colonies are more widely spaced in the uncultivated field, a finding interpreted as a function of a reduced food supply, especially grass seeds, compared to agricultural contexts. Mounds are spaced an average of 20 m in the

Table 4.6. Summary of mound and clearing features for active and abandoned colonies.

Property	Uncultivated Field				Fallow Field				Cultivated Field	
	Active (n=16)		Abandoned (n=6)		Active (n=40)		Abandoned (n=5)		Active (n=6)	
	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Nearest Neighbor										
Distance (m)	13-30.6	20.3 (5.4)	not present	not present	8.0-22.0	13.3 (3.4)	not present	not present	12.5-18.1	14.8 (2.6)
Entryways										
Number	1-15	5.3 (3.5)	not present	not present	1-27	10.3 (5.1)	not present	not present	6-22	10.2 (6)
Aspect (deg)	89-175	129 (28)	not present	not present	46-175	121 (29)	not present	not present	87-138	112 (22)
Clearings										
Length (m)	2.5-5.3	3.4 (0.9)	1.7-3.8	3.2 (0.8)	1.7-5.0	2.9 (0.8)	1.8-2.9	2.4 (0.4)	2.2-3.9	2.9 (0.6)
Width (m)	1.8-5.1	3.0 (0.9)	1.5-3.5	3.0 (0.8)	1.2-4.2	2.5 (0.8)	1.5-2.7	1.9 (0.5)	1.9-3.9	2.8 (0.7)
Area (m2)	3.2-21.0	8.8 (5.0)	2.0-10.2	7.9 (3.2)	1.6-16.6	6.1 (3.6)	2.1-6.1	3.7 (1.5)	3.2-11.9	6.7 (3.0)
Mounds										
Length (m)	0.8-1.8	1.2 (0.3)	0.5-1.5	1.2 (0.4)	0.6-1.3	0.9 (0.2)	0.5-0.9	0.7 (0.1)	0.8-1.1	0.9 (0.1)
Width (m)	0.7-1.7	1.0 (0.3)	0.5-1.4	1.1 (0.4)	0.4-1.2	0.8 (0.2)	0.5-0.8	0.6 (0.1)	0.5-0.8	0.6 (0.1)
Area (m2)	0.4-2.4	1.0 (0.5)	0.2-1.6	1.1 (0.6)	0.2-1.2	0.5 (0.2)	0.2-0.5	0.4 (0.1)	0.3-0.7	0.5 (0.1)
Height (m)	0.18-0.33	0.25 (0.04)	0.03-0.21	0.13 (0.07)	0.14-0.29	0.20 (0.04)	0.02-0.10	0.06 (0.03)	0.14-0.19	0.17 (0.02)
Volume (m3)	0.03-0.26	0.08 (0.06)	0.002-0.11	0.05 (0.04)	0.005-0.11	0.04 (0.02)	0.001-0.01	0.007 (0.005)	0.01-0.03	0.02 (0.01)
Surface Cover (%)**	60-90	88 (10)	30-50	38 (10)	30-95	70 (16)	0-25	14 (11)	20-85	48 (24)

Table 4.7. Ubiquity values for vegetation within 5 m of active and abandoned colonies.

Vegetation		Uncultivated Field		Fallow Field		Cultivated Field
		Active	Abandoned	Active	Abandoned	Active
Big sagebrush	*Artemesia tridentata*	100	100	5	17	
Rabbitbrush	*Chrysothamnus nauseosus*	44	50	57	33	
Juniper	*Juniperus*	13				
Western wheat grass	*Agropyron smithii*	13		15		
Blue gramma	*Bouteloua gracilis*	25	33			
Broom snakeweed	*Gutierezia sarothrae*	13	67	3	17	
Mullen	*Verbascum*	19		65	33	
Curlycup gumweed	*Grendelia aphanactis*			63	50	33
Cheat grass	*Bromus tectorum*			65	33	33
Squirrel tail	*Hordeum jubatum*			10	33	
Bind weed	*Ipomoea purpure*			40	33	100
Miscellaneous grasses		81	67	23	50	

Note: Ubiquity values represent a percentage of colonies in each context with these plant associations.

uncultivated fields, and 13 m and 15 m in the fallow and cultivated fields, respectively. The wider spacing in the uncultivated field may also reflect long-term competition effects because larger colonies can prevent younger ones from surviving. Previous studies have shown that survival rates are very low for colonies younger than two years, but thereafter the likelihood for survival greatly increases (Nagel and Rettenmeyer 1973; Gordon 1991; Keeler 1993).

Entryways were concentrated on the southeast side of mounds, which supports the finding of previous studies that mound entries are built to take advantage of early morning solar heating. Observations at mounds throughout other parts of Zuni Reservation indicate a southeast orientation for most entryways, regardless of the aspect of the terrain where mounds are built. Interestingly, mounds in agricultural settings have twice as many entryways as those of the uncultivated field, with an average of 10 vs. 5 entryways. Older colonies often have much broader openings to accommodate the movement of their larger populations, and multiple openings on a mound surface often connect to a large crack-like passageway a few centimeters below surface. Most entryways, regardless of size, are built in the basal sector of the mound, usually about one-fourth to one-third of the way up from the bottom of the mound.

Some mounds had one or more north-facing entryways, but these are probably relicts from *moundlets* representing incipient loci of earthen deposition from an early stage of mound construction. We observed such moundlets in recently plowed fields, prior to their coalescence into a single mound. Through time, it appears that southeast-facing entryways become dominant and most north-facing ones are plugged and abandoned.

Mounds in the uncultivated field tend to be larger than those of agricultural contexts, where natural vegetation has been removed and plowing has disrupted their nests. Because of their mean greater age, mounds in the uncultivated field have over twice the average volume (0.08 m^3) than those in the fallow field, and the latter have nearly twice the volume of those in the cultivated field. Mound construction rates vary greatly between the three parcels, as discussed below in the section on estimated soil turnover rates. A greater percentage of the surface of mounds in the uncultivated area are covered by fine gravel and granules, which suggests that their mound surfaces are more stable and construction rates are reduced for these mounds.

Mean clearing size around active mounds in the uncultivated field is also larger than that of active mounds in agricultural contexts. Clearings average 8.8 m^2 for colonies in the uncultivated field, and 6.1 m^2 and 6.7 m^2 for fallow and cultivated fields, respectively. Because mean clearing areas do not differ as greatly as mound volumes, the rate of denudation around the mound must have slowed through time relative to mound construction activity. The larger size of clearings in the cultivated field relative to the fallow field is due in part to our weeding activity in the maize field. We did, however, observe ants actively dismantling emerging maize seedlings around their mound, so the clearings are not the result of weeding alone.

Regression analysis was conducted to examine the relationship between mound volume and clearing area. Both properties are a function of colony age (except for colonies that have moved into abandoned nests) and population size. Older and more populous colonies tend to have larger mounds and clearings, but the rates of mound-building and vegetation clearing slow through time. Mound volume and clearing area were best correlated in the uncultivated field ($r^2 = 0.60^{**}$), followed by the fallow ($r^2 = 0.37^{*}$) and cultivated fields ($r^2 = 0.20$). The greater correlation for colonies in the uncultivated fields (the area least disturbed by human activity) indicates that relative differences between mound volume and clearing area tend to narrow through time, so these properties become increasingly better predictors of one another. This finding suggests that through time, the relative energy expended on these two activities approaches a level of quasi-equilibrium, one that in all likelihood confers a competitive advantage.

Sagebrush was associated with all colonies in the uncultivated area, which contrasts with only 5% of active mounds and 17% of the abandoned mounds in the fallow field having associated sagebrush (see Table 4.7). Colonies in the uncultivated field were the only ones with associated blue gramma and juniper. Even though juniper was only infrequently found in the uncultivated and fallow fields, we observed ants actively carrying juniper berries to their nest when they were available. Rabbitbrush was found near about one-third to one-half the colonies in the uncultivated and fallow fields. Snakeweed was a more common associate of abandoned mounds of both field types, which indicates that it is well suited to the soil of abandoned clearings. Plants that thrive in disturbed areas (curlycup gumweed, cheat grass, squirrel tail, and bind weed) were only found near colonies of agricultural contexts, and mullen was more commonly associated with colonies in the fallow field than those of the uncultivated field. Overall, the fallow field appeared to have the richest food supply for the western harvester colonies, which accounts for its higher colony density.

Estimated Soil Turnover Rates

Even though mounds in the uncultivated field tend to be larger in volume than those of agricultural contexts, the latter's relative youth (nine years for the fallow field and one year for the cultivated field) means that mound construction activity, and thus the soil turnover rate, is actually much higher than for the uncultivated field. Based on total mound volumes for uncultivated, fallow and cultivated fields, soil turnover rates were estimated at 35, 192, and 590 m^3/ha/1000 years for each respective parcel (Table 4.8). Two assumptions were necessary in making these calculations. First, mound fill is assumed to originate from below surface rather than from the nearby surface. Our brief observations of ant behavior suggest this assumption is largely valid, even though some plant debris, insects, and in all likelihood, surface-derived gravel have been incorporated into the fill. Secondly, the total volume of mounds in the uncultivated field, omitting that of abandoned mounds, is assumed to represent 40 years of mound construction, a figure that was rounded down from the mean colony lifespan of 43.5 years calculated by Keeler (1993) in Nebraska. Because we lack data on the actual mean colony lifespan for our study, our assumed value of 40 years is the weakest part of our estimation of soil turnover rates. If the true mean age of colonies in the uncultivated

Table 4.8. Mean values for mound clearing attributes, spacing, and soil turnover rates.

Field Plots	Area of Clearing (m)	Height of Mound (m)	Area of Mound (m^2)	Volume of Mound (m^3)	Surface Covered by Mounds (%)	Surface Covered by Clearings (%)	Mean Nearest Neighbor (m)	Soil Turnover Rate (m^3/ha/1000y)	Projected Time for Entire Surface to be Ant-affected (y)
Uncultivated	8.8	0.25	0.98	0.076	0.18	1.6	20.3	35	2500
Fallow	6.1	0.2	0.54	0.035	0.26	3.0	13.3	192	300
Cultivated	6.7	0.17	0.46	0.019	0.14	2.2	18.1	590	50

field is different, then the rate would need to be adjusted accordingly. If, for example, the mean colony age were found to be only 20 years, then the turnover rate would double to 70 m^3/ha/1000 years. Forty years seems to be a reasonable estimate, and it is in the range of colony age estimates (17 to 50 years) provided by Lyons (1994). It is likely that the turnover rate for the uncultivated field is near or at a state of equilibrium, due to long time colonies have had to adjust to a steady food supply reflecting more stable vegetation conditions. In the last few decades or centuries the amount of grazing activity is probably the greatest perturbation to the turnover rate in the uncultivated field flats.

The intermediate soil turnover rate (192 m^3/ha/1000y) for the fallow field corresponds to an intermediate level of effort in mound construction. If the fallow field is not returned to agricultural production, and sagebrush were permitted to displace much of the grassy vegetation, it is likely that mound construction rates would slow and colonies would become more widely spaced as colonies adjust to the diminished food supply.

The high turnover rate (590 m^3/ha/1000y) for the cultivated field reflects an energetic response in relocating colonies in the year after plowing disturbed their mounds and upper nests. Because populations for these mounds are substantial, consisting of several thousand individuals rather than a few hundred as expected for a new colony, these mounds may reflect relocated or disturbed nests rather than new colonies. There are number of important implications of such high turnover rates. First, nutrient cycling is much greater so there is a greater benefit for soil productivity, as deeply buried nutrients are move up into the major rooting zone. Secondly, the higher turnover rate means that there is also a higher rate of soil mixing, and thus horizonation is countered to a greater degree. Despite this effect, the widespread presence of an argillic horizon both below the surface cultivated field indicates that subsurface horizonation is a more dominant long-term factor than pedoturbation.

Ants Influences at the Soil Landscape Scale

Vegetation clearings around mounds comprise 1.6% of the uncultivated field, 3 percent of the fallow field, and 2.2 percent of the cultivated field (see Table 4.1). Using these percentages as instantaneous measures of soil influence by ants, we projected the time for the entire surface to become affected by ant activity for the different field types. In making these estimates we assume that: (1) mean colony age is 40 years (rounded from the 43.5 years found by Keeler (1993) in Nebraska); and (2) ant clearings do not duplicate those of previous nests within a clearing cycle (that is, clearings are always placed on new territory until the entire surface has been covered by clearings). It is recognized that the latter assumption is not truly met, but it is necessary to project how ant influences can be projected to the landscape scale. In reality, clearings must overlap previous ones in varying degrees in a patchwork-like, mosaic fashion. The projected time for the entire surface to become ant-affected was derived using the following formula: (t/c)a, where t = total area (%), c = cleared area (%), and a = average age of colony (y). Using this formula we projected that the entire surface of the uncultivated field could have been affected by ant clearing activity in the last 2500 years, calculated as follows: (100%/1.6%)/40 y = 2500 y.

It is interesting to note that the roughly 2500-year estimate for uncultivated rangeland is within the approximate time frame of farming activity documented on the Zuni Reservation. The true rate was probably much less than a 2500-year cycle in the past, because ants have had to compete with livestock for food since the Spanish introduced sheep and cattle to the Zuni several centuries ago. Sheep and cattle have significantly altered plant distributions through overgrazing of grasses. If the effects of overgrazing by livestock could be removed from the equation, we would obtain a more realistic measure of ant activity for prehistoric conditions. We expect that the rate at which ant clearings affected the surface was much faster prior to livestock introduction, because thicker grasser cover would have supported higher ant population densities. It would be useful to repeat this study in an exclosure where livestock has been excluded, if such an area could be found. Despite the uncertainties that exist in estimating vegetation clearance rates, there is no doubt that ants have had an appreciable long-term effect on soil productivity over the Holocene.

As with the elevated soil turnover rates, farming has had an accelerating effect on the rate at which ants influence the soil surface by clearing vegetation. The entire surface, if maintained in such a state, could be modified in about 300 years in the fallow field and 50 years in the cultivated field. The latter figure should be viewed as only a rough approximation for several reasons: (1) our weeding activity extended vegetation clearances around ant mounds; (2) clearings were much less distinct and thus more difficult to measure in the cultivated field than in uncultivated and fallow fields; and (3) potential sampling error resulting from the small sample size of clearings in the cultivated field (n=6) relative to the fallow (n=40) and uncultivated (n=16) fields.

Admittedly, there are a number of uncertainties in the projecting ant influences from existing cleared areas to the broader landscape of the different field types. Although we cannot adequately control all factors pertinent to vegetation clearance rates associated with ant activity, we still consider our estimates to be reasonable approximations. Harvester ants appear to have modified the entire landscape several times over during the Holocene, and their influence is greatly accelerated in agricultural contexts.

SUMMARY AND CONCLUSIONS

This investigation examined selected interactions between soil properties, vegetation associations, and colonies of the western harvester ant. The overall effect of ants is to increase the porosity, aeration, hydraulic conductivity, nutrient status, and tilth of the soil, especially near the surface where their burrowing activities are concentrated. Interestingly, Zuni farmers are aware that ant mound soils have increased soil fertility levels. Compared to reference soils, we found that ant mound soils generally have lower bulk densities, pHs, and clay contents, and higher levels of organic carbon, nitrogen, and available and total phosphorus, sand, and gravel. These changes are generally consistent with previous studies of ant influences on soil. Highly decomposed organic matter is strongly associated with the walls of ant chambers and tunnels, as indicated by both soil thin sections and low C:N ratios. Ants expend more energy in burrowing and mound construction activities in cultivated and fallow fields and their colonies are more closely spaced in these locales, because of the concentrated available food supply in active and fallow agricultural land. Consequently, the soil turnover and nutrient cycling rates is accelerated in these contexts as well. Ant effects on surface soils may extend to entire landscapes within 50 to 2500 years, with the most rapid rates associated with cultivated fields. Additional studies are needed to assess how western harvester ants influence and interact with plants and soils in other environmental contexts.

REFERENCES

Adamson, A. M. (1943). Termites and the Fertility of Soils. *Tropical Agriculture* 20, 107-11

Arizona-Sonoran Desert Museum (1998). *A Natural History of the Sonoran Desert.* Arizona-Sonoran Desert Museum Press, Tucson.

Bear, F. E. (1927). *Soil Management* (2nd Ed.). John Wiley and Sons, New York.

Blackburn, T. (1976). A Query Regarding the Possible Hallucinogenic Effects of Ant Ingestion in South-central Califorina. *The Journal of California Anthropology* 3(2): 78-81.

Blake, G. R., and K. H. Hartge (1986). Bulk Density. *In Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods.* (A. Klute, ed.), Vol. 9, pp. 363-375. American Society of Agronomy and Soil Science Society of America, Madison.

Brady, N. C., and R. R. Weil (1999). *The Nature and Properties of Soils* (12th Ed.). Prentice Hall, Upper Saddle River, New Jersey.

Bunzel, R. L. (1932). *Introduction to Zuni Ceremonialism, Zuni Origin Myths, and Zuni Ritual Poetry.* 47th Annual Report of the Bureau of American Ethnology, 1929-1930, Smithsonian Institution, Washington (reprinted by the University of New Mexico Press in 1992).

Byars, L. F. (1930). *An Ecological Study of the Ants of Boulder County.* Master's thesis, The University of Colorado, Boulder.

Carlson, S. R., and W. G. Whitford (1991). Ant Mound Influence on Vegetation and Soils in a Semiarid Mountain Ecosystem. *The American Midland Naturalist* 126: 125-139.

Clark, P. J., and F. C. Evans (1954). Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations. *Ecology* 35: 445-453.

Cole, A. C., Jr. (1932). The Relation of the Ant, *Pogonomyrmex Occidentalis* Cr., to Its Habitat. *Ohio Journal of Science* 32: 133-146.

Cole, A. C., Jr. (1968). *Pogonomyrmex Harvester Ants: A Study of the Genus in North America*, The University of Tennessee Press, Knoxville.

Cole, B. J., and D. C. Wiernasz (2000). The Nature of Ant Colony Success (response to Fjerdingstad and Keller). *Science* 287: 1363b.

Culver, D. C., and A. J. Beattie (1983). Effects of Ant Mounds on Soil Chemistry and Vegetation Patterns in a Colorado Montane Meadow. *Ecology* 64: 485-492.

Czervinski, Z., H. Jakubczyk, and J. Petal (1971). Influence of Ant Hills on the Meadow Soils. *Pedobiologia* 7: 277-285.

Dick, W. A., and M. A. Tabatabai (1977). An Alkaline Oxidation Method for Determination of Total Phosphorus in Soils. *Soil Science Society of America Journal* 41: 511-514.

Doerge, T. A. (1985). "A Summary of Soil Test Information for Arizona's Surface Agricultural Soils: 1965-1984," Department of Soil and Water Science, University of Arizona, Tucson.

Dumpert, K. (1981). *The Social Biology of Ants.* Pitman Advanced Publishing Program, Boston.

Ferguson, T. J., and E. R. Hart (1985). *A Zuni Atlas.* University of Oklahoma Press, Norman.

Foth, H. D., and Boyd G. Ellis (1988). *Soil Fertility.* John Wiley and Sons, New York.

Gee, G. W., and J. W. Bauder (1986). Particle-size Analysis. *In Methods of Soil Analysis. Physical and Mineralogical Methods* (A. Klute, ed.), Vol. Monograph No. 9, Part 1, pp. 383-411. American Society of Agronomy and Soil Science Society of America, Madison.

Gentry, J. B., and K. L. Stiritz (1972). The Role of the Florid Harvester Ant, Pogonomyrmex badius, in Old Field Mineral Nutrient Relationships. *Environmental Entomology* 1: 39-41.

Gilbert, H. (1960). Sheridan Man Conducts Survey of Ant Hills on Wyoming Ranges. *Wyoming Stockman-Farmer* 66: 29, 63.

Gordon, D. M. (1991). Behavioral Flexibility and the Foraging Ecology of Seed-eating Ants. *The American Naturalist* 138: 379-411.

Green, W. P., D. E. Pettry, and R. E. Switzer (1998). Formicarious Pedons, the Initial Effect of Mound-Building Ants on Soils. *Soil Survey Horizons* 39: 33-44.

Gregg, R. E. (1963). *The Ants of Colorado.* University of Colorado Press, Boulder.

Groark, K. P. (1996). Ritual and Therapeutic Use of "Hallucinogenic" Harvester Ants (*Pogonomyrmex*) in Native South-central California. *Journal of Enthobiology* 16(1): 1-29.

Hesse, P. R. (1955). A Chemical and Physical Study of the Soils of Termite Mounds of East Africa. *Journal of Ecology* 43: 449-461.

Hölldobler, B, and E. O. Wilson (1990). *The Ants.* Belknap Press, Harvard University, Cambridge.

Hutchins, R. E. (1967). *The Ant Realm.* Dodd, Mead & Company, New York.

Huxley, C. R., and D. F. Cutler, ed. (1991). *Ant-Plant Interactions.* Oxford University Press, Oxford.

Jakubczyk, H., Z. Czerwinski, and J. Petal (1972). Ants as Agents of the Soil Habitat Changes. *Ekologia polska* 20: 153-161.

Jolivet, P. (1996). *Ants and Plants: An Example of Coevolution.* Backhuys Publishers, Leiden.

Keeler, K. H. (1993). Fifteen Years of Colony Dynamics in *Pogonomyrmex occidentalis*, the Western Harvester Ant, in Western Nebraska. *The Southwestern Naturalist* 38: 286-289.

Lavigne, R. J. (1969). Bionomics and Nest Structure of *Pogonomyrmex occidentalis. Annals of the Entomological Society of America* 62: 1166-1175.

Lee, K. E., and T. G. Wood (1971). Physical and Chemical Effects on Soils of Some Australian Termites and Their Pedological Significance. *Pedobiologia* 11:376-409.

Levan, M. A., and E. L. Stone (1983). Soil Modification by Colonies of Black Meadow Ants in a New York Old Field. *Soil Science Society of America Journal* 47: 1192-1195.

Lobry de Brun, L. A., and A. J. Conacher (1990). The Role of Termites and Ants in Soil Modification. *Australian Journal of Soil Research* 28: 55-93.

Lockaby, B. G., and J. C. Adams (1985). Pedoturbation of a Forest Soil by Fire Ants. *Soil Science Society of America Journal* 49: 220-223.

Lyford, W. H. (1963). Importance of Ants to Brown Podzolic Soil Genesis in New England. *Harvard Forest Paper* 7: 1-18.

Lyons, S. (1994). Low-tech ants give a high-tech Idaho lab fits. *High Country News* 26(11)1-2. (http:/www.hcn.org/1994/jun13/dir/wr_p95b.html)

MacKay, W. P., and E. E. MacKay (1984). Why Do Harvester Ants Store Seeds in Their Nests? *Sociobiology* 9: 31-47.

Mandel, R. D., and C. J. Sorenson (1982). The Role of the Western Harvester Ant (*Pogonomyrmex occidentalis*) in Soil Formation. *Soil Science of America Journal* 46: 785-788.

McCook, H. C. (1882). *The Honey Ants and the Occident Ants.* J. B. Lippincott & Co., Philadelphia.

McLean, E. O. (1982). Soil pH and Lime Requirements. *In Methods of Soil Analysis. Chemical and Microbiological Properties* (A. L. Page, R. H. Miller, and D. R. Keeney, ed.), Agronomy Monograph No. 9, Part 2, pp. 199-222. American Society of Agronomy and Soil Science Society of America, Madison.

Moody, J. V., and O. F. Franke (1982). *The Ants (Hymenoptera, Formicidae) of Western Texas.* Texas Tech Press, Lubbock.

Nagel, H. G., and C. W. Rettenmeyer (1973). Nuptial Flights, Reproductive Behavior and Colony Founding of the Western Harvester Ant, *Pogonomyrmex occidentalis* (Hymenoptera: Formicidae). *Journal of the Kansas Entomological Society* 46: 82-101.

National Soil Survey Center (1996). *Soil Survey Laboratory Methods Manual.* U. S. Department of Agriculture, Natural Resources Conservation Service, Lincoln, Nebraska.

Petal, J. (1978). The Role of Ants in Ecosystems. *In Production Ecology of Ants and Termites.* (M. V. Brian, ed.), Vol. 13, pp. 292-325. Cambridge University Press, Cambridge.

Pomeroy, D. E. (1976). Some Effects of Mound-building Termites on Soils in Uganda. *Journal of Soil Science* 27: 377-394.

Porter, S. D., and C. D. Jorgensen (1988). Longevity of Harvester Ant Colonies in Southern Idaho. *Journal of Range Management* 41: 104-107.

Robinson, J. B. D. (1958). Some Chemical Characteristics of 'Termite Soils' in Kenya Coffee Fields. *Journal of Soil Science* 9: 58-65.

Rogers, L. E. (1972). *The Ecological Effects of the Western Harvester Ant (Pogonomyrmex occidentialis) in the Shortgrass Plains Ecosystem.* USA/IBP Grassland Biome Cambridge.

Rogers, L. E. (1974). Foraging Activity of the Western Harvester Ant in the Short Grass Plains Ecosystem. *Environmental Entomology* 3: 420-424.

Salem, M. Z., and F. D. Hole (1968). Ant (*Formica exsectoides*) Pedoturbation in a Forest Soil. *Soil Science Society of America Proceedings* 32: 563-567.

Schmidt, J. O., P. J. Schmidt, and R. R. Snelling (1986). Pogonomyrmex occidentalis, An Addition to the Ant Fauna of Mexico, with Notes on Other Species of harvester Ants from Mexico (Hymenoptera: Formicidae). *Southwest Naturalist* 31: 395-396.

Scott, H. W. (1951). The Geological Work of the Mound-building Ants in Western United States. *Journal of Geology* 59: 173-175.

Sharp, L. A., and William F. Barr (1960). Preliminary Investigations of Harvester Ants on Southern Idaho Rangelands. *Journal of Range Management* 13: 131-134.

Southwood, T. R. E. (1973). *Ecological Methods with Particular Reference to Insects* (2nd Ed.) Chapman & Hall, London.

Spangler, H. G., and C. W. Rettenmeyer (1966). The function of ammochaetae or psammophores of harvester ants, *Pogonomyrmex* spp. *Journal of the Kansas Entomological Society* 39: 739-745.

Spangler, H. G. (1967). Ant Stridulations and Their Synchronization with Abdominal Movement. *Science* 155: 1687-1689.

Spangler, H. G. (1973). Vibration Aids Soil Manipulation in Hymenoptera. *Journal of the Kansas Entomological Society* 46: 157-160.

Soil Survey Staff (1993). "Soil Survey Manual," 2nd Ed. U. S. Department of Agriculture, United States Government Printing Office, Washington.

Soil Survey Staff (1998). "Keys to Soil Taxonomy," 8th Ed. U. S. Department of Agriculture, Natural Resources Conservation Service, Washington.

Soil Survey Staff (1999). *A Basic System of Soil Classification for Making and Interpreting Soil Surveys* (2nd Ed.) U. S. Department of Agriculture, United States Government Printing Office, Washington, D.C.

Stevenson, M. C. (1904). *The Zuni Indians: Their Mythology, Esoteric Fraternities, and Ceremonies.* 23rd Annual Report of the Bureau of American Ethnology for the Years 1889-1990. Smithsonian Institution, Washington.

Stoops, G. (1964). Applications of Some Pedological methods to the Analysis of Termite Mounds. *In Etudes sur les Termites Africains* (A. Bouillon, ed.), pp. 379-398. Masson et Cie, Paris.

Sudd, J. H., and Nigel R. Franks (1987). *The Behavioral Ecology of Ants.* Blackie & Sons Limited, Glasgow.

Taber, S. W. (1998). *The World of the Harvester Ants.* Texas A&M Press, College Station, Texas.

Taylor, F. (1978). Foraging Behavior of Ants: Theoretical Considerations. *Journal of Theoretical Biology* 71: 541-565.

Tedlock, D. (1979). Zuni Religion and World View. In *Handbook of North American Indians. Vol. 9. Southwest* (A. Ortiz, ed.), pp.499-508. Smithsonian Institution, Washington.

Thorp, J. (1949). Effects of Certain Animals that Live in Soil. *Science Monthly* 68: 180-191.

Tisdale, S., W. L. Nelson, and J. D. Beaton (1985). *Soil Fertility and Fertilizers* (4th/Ed.). Macmillan Publishing Company, New York.

Wali, M. K., and P. B. Kannowski (1975). Prairie Ant Mound Ecology: Interrelationships of Microclimate, Soils and Vegetation. *In Prairie: A Multiple View* (M. K. Wali, ed.), pp. 155-169. The University of North Dakota Press, Grand Forks.

Wang, D., K. McSweeney, B. Lowery, and J. M. Norman (1995). Nest Structure of Ant *Lasius neoniger* Emery and Its Implications to Soil Modification. *Geoderma* 66: 259-272.

Watson, J. P. (1962). The Soil Below a Termite Mound. *Journal of Soil Science* 13: 46-51.

Wheeler, G., and J. Wheeler (1973). *Ants of the Deep Canyon.* Philip L. Boyd Deep Canyon Desert Research Center, University of California, Riverside.

Wheeler, G. C., and J. Wheeler (1963). *The Ants of North Dakota.* University of North Dakota Press, Grand Forks.

Wheeler, G. C., and J. N. Wheeler (1986). *The Ants of Nevada.* Natural History Museum of Los Angeles County, Los Angeles.

Wheeler, W. M. (1902). A New Agricultural Ant from Texas, With Remarks on the Known North-American Species. *American Naturalist* 36: 387-393.

Wheeler, W. M. (1910). Ants: *Their Structure, Development and Behavior.* The Columbia University Press, New York.

Whiteford, W. G., and M. Bryant (1979). Behavior of a Predator and its Prey: the Horned Lizard (*Phrynosoma cornutum*) and Harvester Ants (*Pogonomyrmex* spp.). *Ecology* 60(4): 686-694

Whitford, W. G., D. Schaefer, and W. Wisdom (1986). Soil Movement by Desert Ants. *The Southwestern Naturalist* 31: 273-274.

Wight, J. R., and J. T. Nichols (1966). Effects of Harvester Ants on Production of A Saltbush Community. *Journal of Wildlife Management* 19: 68-71.

Wiken, E. B., K. Broersma, L. M. Lavkulich, and L. Farstad (1976). Biosynthetic Alteration in a British Columbia Soil by Ants (Formica fusca *Linnè*). *Soil Science Society of America Journal* 40: 422-426.

Wild, A. (1993). *Soils and Environment: An Introduction*. Cambridge University Press, Cambridge.

Williams, M. A. J. (1968). Termites and Soil Development Near Brock's Creek, Northern Territory. *Australian Journal of Science* 31: 153-154.

Wilson, E. O. (1958). A Chemical Releaser of Alarm and Digging Behavior in the Ant *Pogonomyrmex badius* (Latreille). *Psyche* 65: 41-51.

Wood, T. G., and Sands (1978). The Role of Termites in Ecosystems. *In Production Ecology of Ants and Termites*, (M. V. Brian, ed.), Vol. 13, pp. 245-292. Cambridge University Press, Cambridge.

Wu, H. J. (1990). Disk Clearing Behavior of the Red Harvester Ant, *Pogonomyrmex barbatus* Smith. *Bulletin of the Institute of Zoology, Academia Sinica* 29: 153-164.

Young, J., and D. E. Howell (1964). *Ants of Oklahoma.* Oklahoma State University, Experiment Station, Stillwater.

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CHAPTER 5
CONCLUSIONS

In this dissertation I evaluated some of the major influences that humans and western harvester ants have had on physical and chemical soil properties in the context of American Indian agricultural settings in the Southwest. This research was divided into three separate soil studies, including: (1) modern Zuni runoff agricultural soils in New Mexico (Zuni); (2) ancient rock mulch agricultural soils near Safford, Arizona; and (3) western harvester ant influences on soils in a Zuni field. Table 5.1 presents selected comparisons of soil properties for the three studies.

Results of the Zuni study indicate that cultivation has largely resulted in positive effects on soil properties important for soil productivity. Two of the major beneficial changes include: (1) thickened A horizons, caused both by plowing and human manipulation to direct runoff water and organic-rich sediment onto agricultural fields; and (2) organic matter coatings on grains and granular peds in many cultivated fields. Soil pH levels were commonly increased in cultivated soils due to deposition of calcareous sediment, but not at levels that might cause structural disaggregation or significantly limit maize production. On average, organic C and N, and total and available P concentrations are slightly reduced in cultivated soils, but generally not at statistically significant levels. Importantly, no statistical differences were found in all soil properties summarized in Table 5.1 for the broadest scale of analysis, that for the unpaired cultivated and uncultivated fields.

Two potential negative influences of cultivation were identified in the Zuni study. These include increased compaction and reduced granularity in cultivated soils. These soil

Table 5.1. Comparison of cultivated, uncultivated, and ant-affected soils of from the Zuni and Safford project areas.

Soil Property		Paired Zuni Fields			Unpaired Zuni Fields			Safford Grid and Terrace Alignments						Ant-affected and Other Soils			
		Cult. (n=3)	Uncult. (n=3)	%Diff.	Cult. (n=(9)	Uncult. (n=10)	%Diff.	Grid (n=8)	Uncult. (n=6)	%Diff.	Terr. (=3)	Uncult. (n=3)	%Diff.	SE1/4 Mound	Clearing	Fallow	Uncult.
pH (1)		7.2	7.0	-- *	7.0	6.7	--	7.7	8.4	-- **	7.7	8.1	-- *	6.0	6.3	6.8	6.5
Organic C	(g/kg)	11.3	13.3	-18	12.2	13.1	-7	5.2	4.0	30 *	5.1	8.7	-41	9.9	6.4	8.7	17.3
N	(g/kg)	0.87	0.97	-11 *	0.90	0.99	-9	0.49	0.42	17	0.71	0.64	11	1.06	0.49	0.76	1.21
C:N Ratio		12.7	13.6	-7 *	13.3	13.0	2	15.8	20	-21	10.9	12.7	-14	9.2	13.4	11.5	14.6
Available P	(mg/kg)	8.3	9.1	-9	9.5	13.7	-31	13.1	6.3	108 *	17.7	11.5	54	114	16.3	8.7	17.3
Total P	(mg/kg)	324	321	1	294	322	-9	603	700	-14 *	604	461	31	768	250	237	344
Bulk Den.	(g/cm3)	1.56	1.45	8 *	1.48	1.43	3	1.39	1.34	4	1.37	1.38	-1	1.65	1.48	1.45	1.49
Sand	(%)	46	50	8	57	49	17	45	49	-8	52	44	18	57	63	67	49
Silt	(%)	31	31	-1	27	31	-14	31	36	-3	40	39	3	29	27	19	35
Clay	(%)	22	19	17	17	21	-19	18	13	38	9	17	-47	14	10	12	16
				* $\alpha = 0.2$			* $\alpha = 0.1$			* $\alpha = 0.1$ ** $\alpha = 0.01$			* $\alpha = 0.2$	Note: fallow soil is for the Ap horizon; uncult. and clearing soils are for similar depths			

(1) % difference not shown for pH due to log scale of units

changes are mainly the result of two processes, structural disaggregation caused by plowing and incorporation of unstructured (or massive) fresh sediments carried by runoff water. Compaction and reduced granularity are usually viewed as a negative consequence of farming in most agricultural systems, especially heavily mechanized systems in more humid regions. But in Zuni agricultural fields, where rainfall has a particularly strong influence on agricultural productivity, some compaction and reduced granularity may actually be beneficial for agriculture by aiding moisture retention in the rooting zone. And because cultivated soils are generally friable to very friable, it is unlikely that compaction at the levels found (8.5% for paired fields and 3.5% for unpaired fields) impede maize root growth to any significant degree if at all. Additional research is needed to assess the possibility that some compaction and reduced granularity may be beneficial to agriculture. This research should focus on measuring pore continuity and size distributions, the influence of bulk density on maize root growth and distributions with depth, and soil:water relationships. I am now doing research on the latter topic to document water infiltration rates, saturated and unsaturated hydraulic conduction, and plant available moisture levels.

In attempting to evaluate anthropogenic effects on soil properties of Zuni agricultural runoff soils, it was difficult to impossible to adequately hold the non-anthropogenic factors constant, or at least approximately so, because of natural soil variability (especially that resulting in horizontal and vertical discontinuities in soil texture caused by alluvial sedimentation processes) exists over short distances. Paired field comparisons assume that the uncultivated samples are valid controls, but this assumption very often may not be met. The biggest challenge in the paired field sampling approach is finding suitable uncultivated samples to serve as controls for evaluating cultivation effects. Cultivated soils in paired fields sometimes appear to be more degraded, but many of the differences are explained by natural variability in soil texture rather than anthropogenic effects.

The Safford study focused on soils associated with extensive rock mulch features (grids, terraces, and rock piles) built by ancient farmers to conserve water and nutrients in the shallow rooting zone. Existing native vegetation is concentrated in the rock mulch features today, thus showing that cobble mulch continues to be effective at conserving soil moisture in the thin rooting zone. Agricultural soils in the Safford study generally had reduced soil pH, at levels beneficial for crop production due to increased plant availability for many essential nutrients. Relative to uncultivated soils, mulched soils tend to have elevated C, N, and available P concentrations and no evidence of soil compaction. Unlike at Zuni, where maize is the principal crop, the crop(s) grown in the Safford fields is currently unknown, so it much more difficult to evaluate the implications of the soil properties in terms of agricultural production. It is likely that crops, possibly agave other highly drought-tolerant crops, were grown in the Safford fields.

The Safford project area has a much hotter climate and substantially less rainfall than the Zuni area, so native vegetation cover and biomass is much lower at Safford. The much lower plant biomass and runoff rates and higher evaporation and organic matter oxidation rates largely explain the lower organic C and N levels in the Safford soils. And due to the thin soils of Safford above the root-impeding petrocalcic horizon, nutrient levels on a mass quantity basis are much lower in the Safford soils.

Overall, soil properties of the gridded Safford fields indicate they are less productive agriculturally than those of the Zuni area. For both the Zuni and Safford studies, I found no convincing evidence that either runoff or ancient rock mulch farming caused any appreciable soil degradation. American Indian agricultural practices in both project areas appear to have actually improved long-term soil quality for crop production.

The ancillary study was undertaken to measure soil changes caused by the western harvester ant (*Pogonomyrmex occidentalis*). This research focused on measuring their effect on soil fertility in the context of agricultural land use and the rate at which they have modified the landscape. Results indicate that ant-affected soils have elevated levels of organic C, N, and available and total P, so they have a positive influence on agricultural soils. Their effect in enriching nutrients is greatest in the southeast quadrant of the mound, where their activity is focused (see Table 5.1). In addition to nutrient enrichment, ants help to aerate the soil and increase its hydraulic conductivity and water-holding capacity. I projected that ant effects on surface soils extend to entire landscapes within about 2500 years at a minimum, and their effects are greatly accelerated in agricultural contexts, where more food (mainly grass seeds from weedy vegetation and crops) is available. Ant influences, even under relatively natural conditions, occur on a time scale that is well within the agricultural land-use practices in the Zuni area. Overall, western harvester ants appear to have an overall positive long-term influence on agriculture.

This dissertation contributes to a growing body of literature aimed at assessing the biotic factor on soil formation and agricultural productivity. Research on human and ant influences on soil properties is far from exhausted, both in the semiarid Southwestern United States and globally. To better understand anthropogenic influences on agricultural soils, much more work is needed in other environmental and agricultural contexts.

APPENDIX A. SOIL PROFILE DESCRIPTIONS

Safford Soil Study: Pedon Descriptions

Profiles were described by Jonathan A. Sandor and Jeffrey A. Homburg on March 10-13, 1997 in Locality 1, the westernmost part of the agricultural complex. The parent material of all profiles consists of gravelly alluvium derived from Gila Mountain conglomerates and miscellaneous volcanic rocks.

Profile Description 1: Grid interior

Classification: Loamy, mixed, superactive, thermic Typic Petrocalcid (Cave series)
Geomorphic setting: Backslope of alluvial fan, elevation 901 m (2955 ft), 3-4% slope
Agricultural setting: Within grid interior; profile exposed in north wall of Prospector's Pit 1

A 0-2 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly loam, brown (7.5YR 4.5/3) moist; weak medium and coarse plates plus weak to moderate fine and very fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine and few fine roots; few fine and medium tubular pores; 10% gravel; slightly effervescent; moderately alkaline (pH 8.0-8.5; pH 6.5-8.0 under creosotebush); abrupt smooth boundary. Mantled by 80-85% gravel pavement cover, with gravel typically 0.8-2.0 cm in size; crust varies from 1 to 2 cm thick, with an algal crust on the surface, under creosote bush vegetation; some soil is noncalcareous and some thin carbonate coatings noted on parts of the surface.

ABk 2-12 cm. Light brown (7.5YR 6/4) gravelly loam, brown (7.5YR 4/4) moist; weak fine and medium subangular blocks; soft, friable, slightly sticky, slightly plastic; common very fine, fine, and medium roots, with some pockets of many fine to very fine and few large roots; few fine tubular pores; 5-10% gravel and 20% cobbles; strongly effervescent; strongly alkaline (pH 8.0-8.5); clear smooth boundary.

Bk 12-30 cm. Light brown to (7.5YR 6.5/3.5) very gravelly sandy loam; brown (7.5YR 4.5/4) moist; weak fine subangular blocks; soft, friable to very friable, slightly sticky, slightly plastic; common very fine and fine roots; few fine tubular pores; 20% gravel and 25% cobbles; violently effervescent; strongly alkaline (pH 8.0-8.5); abrupt smooth boundary.

Bkm1 30-31 cm (2 to 3 cm thick in places). Matrix is weakly cemented by white (10YR 8/1) carbonate, pink to pinkish gray (7.5YR 7/3) moist (no texture estimate due to cement, but is gravelly/very cobbly); contains some clayey zones of reddish yellow (7.5YR 6/6) stained by iron oxide (?), strong brown (7.5YR 5/6) moist; 20% gravel; root mat on top; strongly effervescent on top to slightly effervescent below, carbonates noted on all sides of gravel and cobbles, but often thickest on top; moderately alkaline (pH 8.0-8.5); abrupt smooth to slightly wavy boundary.

Bkm2 31-71 cm. Matrix is weakly cemented by white (10YR 8/1) and pinkish white (7.5YR 8/2) carbonate, pink to pinkish gray (7.5YR 7/3) moist (no texture estimate due to strong cement, but is gravelly/very cobbly); contains some clayey zones of reddish yellow (7.5YR 6/6) stained by iron oxide (?), strong brown (7.5YR 5/6) moist; 35-40% gravel; rare fine and very fine roots; strongly effervescent, carbonate coatings up to 4 mm thick on the bottom of gravel; moderately alkaline (pH 8.0-8.5); clear smooth boundary.

Bkm3 71-118 cm. Matrix is weakly cemented by white (10YR 8/1) and pinkish white (7.5YR 8/2) carbonate, pink to pinkish gray (7.5YR 7/3) moist (no texture estimate due to strong cement, but is gravelly/very cobbly); contains some clayey zones of reddish yellow (7.5YR 6/6) stained by iron oxide (?), strong brown (7.5YR 5/6) moist; 25% gravel and 15% cobbles; rare fine and very fine roots, but occasionally clustered in pockets; violently effervescent carbonate matrix and effervescent clay plus iron (?); moderately alkaline (pH 8.0-8.5); clear smooth boundary.

B'k 118-125 cm. Light brown (7.5YR 6/3) very gravelly sandy loam, pink to pinkish gray (7.5YR 7/3) moist; massive structure; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots, often in clusters; 15% gravel and 10-15% cobbles; violently effervescent, carbonate coatings on all sides of gravel; moderately alkaline (pH 8.0-8.5); clear smooth boundary.

BCk 125-142 cm. Light brown (7.5YR 6/4) very gravelly sandy loam to very gravelly loamy sand, pink (7.5YR 7/4) moist; massive structure; soft, very friable, slightly sticky, slightly plastic; few very fine and fine roots; 25% gravel and 10% cobbles; strongly to violently effervescent, few carbonate coatings on gravel; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary.

2C 142-162+ cm. Pink (7.5YR 7/3) loamy sand, strong brown to reddish yellow (7.5YR 5.5/6) moist; massive structure; soft, very friable, nonsticky, nonplastic; few very fine and fine roots; 5% gravel; effervescent; moderately alkaline (pH 8.0-8.5).

Profile Description 2: Next to rock pile

Classification: Fine-loamy, mixed, thermic Calcic Paleargid (similar to Pinaleno series; would be classified as a Typic Petroargid if petrocalcic horizon is present in 100-150 cm zone)
Geomorphic setting: Alluvial fan terrace, elevation 899 m (2950 ft), 4% slope
Agricultural setting: Desert pavement near rock pile feature; adjacent to west side of Prospector's Pit 2

A 0-4 cm. Light brown (7.5YR 6/4) loam, brown to strong brown (7.5YR 5/5) moist; moderate medium plates; slightly hard, very friable, slightly sticky, slightly plastic; few fine and very fine roots; many fine to very fine vesicular pores; 10-20% gravel, mainly on the surface; effervescent; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary. Contains few filaments and faint spots of carbonate.

Btk1 4-17 cm. Light brown to reddish yellow (7.5YR 6/5) clay loam, brown to strong brown (7.5YR 4/5) moist; moderate fine subangular blocks; slightly hard, friable, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine and fine roots; few fine tubular pores; 5% gravel; strongly effervescent; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Contains common small (~1mm) masses of carbonate, and the matrix consists of 5-10% carbonate filaments.

Btk2 17-40 cm. Light brown to reddish yellow (7.5YR 6/5) clay loam; strong brown (5YR-7.5YR 5/6) moist; moderate fine subangular blocks; slightly hard, friable, sticky, plastic; many moderately thick clay films on ped faces and pores; few very fine and fine roots; few fine tubular pores; 5% gravel; strongly effervescent; moderately alkaline (pH 8.0-8.5); gradual smooth boundary. Contains common to many soft powdery masses, with few moderately hard masses; several are 5-10 mm across and some are cylindrical in shape.

Btk3 40-59 cm. Light brown to reddish yellow (7.5YR 6/5) loam, strong brown (7.5YR 5/6) moist; moderate fine and medium subangular blocks; hard, firm, sticky, plastic; common thin clay films on ped faces; few very fine and fine roots; few very fine tubular pores; 5% gravel; strongly effervescent matrix, and violently effervescent carbonate masses; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Contains few to common (5-10%) masses of carbonate and some finely disseminated carbonates; some consist of 6-10 mm cylindrical carbonate concentrations, possibly formed in old insect burrows.

2Btk1 59-77 cm. Pinkish gray to light brown (7.5YR 6/3) clay loam, brown to yellowish brown (7.5-10YR 5/3 and 5/4) moist; hard, firm, sticky, plastic; many moderately thick clay films on ped faces; few very fine and fine roots; few very fine tubular pores; <1% gravel; strongly effervescent matrix, and violently effervescent carbonate masses; moderately alkaline (pH 8.0-8.5). Contains few to common moderately hard masses of carbonate.

2Btk2? 77-100+ cm. Pinkish gray to light brown (7.5YR 6/3) clay loam to clay, brown (7.5YR 5/3 and 5/4) moist; weak fine prisms parting to moderate fine and medium subangular blocks; very hard, very firm, very sticky, very plastic; some possible clay coatings on peds; rare fine roots; rare fine tubular pores; strongly effervescent; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Contains few to common seams and filaments of carbonate.

Profile Description 3: Agricultural terrace, upslope of rock alignment

Geomorphic setting: Backslope of fan terrace scarp, 10-11% slope
Agricultural setting: Terrace, 20 cm upslope of rock alignment

A1 0-5 cm. Pinkish gray to light brown (7.5YR 6/3) very gravelly sandy loam to loam, brown (7.5YR 4.5/3) moist; weak to moderate fine and medium subangular blocks and some weak medium plates; soft, very friable, slightly sticky, slightly plastic; few to common very fine roots; few very fine tubular pores; 35% gravel, mainly on the surface; not effervescent; mildly alkaline (pH 7.5); abrupt smooth boundary. This horizon has formed in the upper terrace fill deposit, and it is covered by a patchy gravel pavement.

A2 5-16 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly sandy loam to loam, brown (7.5YR 4.5/3) moist; weak fine subangular blocks and some weak medium plates at the top; slightly hard, very friable, slightly sticky, slightly plastic; common very fine and fine roots; few very fine tubular pores; 15-20% gravel; audibly effervescent; mildly alkaline (pH 7.5); clear smooth boundary. This horizon has formed in the lower terrace fill deposit.

Bk1 16-30 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly sandy loam to loam, brown (7.5YR 4.5/3) moist; weak fine subangular blocks to massive; soft, very friable, slightly sticky, slightly plastic; common very fine and few fine roots; few very fine tubular pores; 25% gravel; strongly effervescent; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Matrix is dominated by finely disseminated carbonates.

2Bk2 30-46 cm. Light brown (7.5YR 6/3.5) extremely gravelly sandy loam, brown (7.5YR 5/4) moist; weak fine subangular blocks to massive; soft, very friable, slightly sticky, slightly plastic; 65% gravel and some cobbles; common very fine and fine roots; strongly effervescent matrix, and violently effervescent; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary. Contains both finely disseminated carbonates and gravel coatings on all sides.

2Bkm 46+ cm. Color of carbonate cement not described, but much lighter than above; massive, cemented; 60-70% gravel; violently effervescent; moderately alkaline (pH 8.0-8.5). This horizon has a laminar cap of carbonate above a massively cemented petrocalcic horizon.

Profile Description 4: Beneath rock alignment between two agricultural terraces

Geomorphic setting: Backslope fan terrace scarp, 10-11% slope
Agricultural setting: Beneath rock alignment

A1 0-5 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly/very cobbly sandy loam to loam, brown to dark brown (7.5YR 4/3) moist; weak fine subangular blocks and some weak medium plates; soft to slightly hard, very friable, slightly sticky, slightly plastic; few fine roots; few very fine tubular pores;

15% gravel, excluding surface gravel in rock alignment; not effervescent; mildly alkaline (pH 7.5); clear smooth boundary. Upper boundary is irregular between rocks.

A2 5-18 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly/very cobbly sandy loam to loam, brown (7.5YR 4.5/3) moist; weak fine subangular blocks; soft, very friable, slightly sticky, slightly plastic; few to common very fine and fine roots; few very fine tubular pores; 25% gravel; not effervescent; mildly alkaline (pH 7.5); clear smooth boundary. Surface gravel in rock alignment extends about 13 to 15 cm below surface.

Bk1 18-27 cm. Pinkish gray to light brown (7.5YR 6/3) gravelly/very cobbly sandy loam, brown (7.5YR 4.5/3.5) moist; weak fine subangular blocks; soft, very friable, slightly sticky, slightly plastic; few to common very fine and few fine roots; few very fine tubular pores; 30% gravel; strongly effervescent; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Carbonate coatings were noted on all sides of gravel.

2Bk2 27-40 cm. Light brown (7.5YR 6/4) extremely gravelly loam to sandy loam, brown (7.5YR 4.5/4) moist; weak fine subangular blocks to massive; soft, very friable, slightly sticky, slightly plastic; 70% gravel and cobbles; few to common very fine and fine roots; strongly effervescent; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary. Carbonate coatings were noted on all sides of gravel.

2Bkm 40+ cm. Color of carbonate cement not described, but much lighter than above; massive, cemented; 60-70% gravel; violently effervescent; moderately alkaline (pH 8.0-8.5). This horizon has a laminar cap of carbonate above a massively cemented petrocalcic horizon.

Profile Description 5: Agricultural terrace, downslope of rock alignment

Geomorphic setting: Backslope of fan terrace scarp, 10-11% slope
Agricultural setting: Terrace, 20 cm downslope of rock alignment

A 0-3 cm. Light brown (7.5YR 6/3.5) gravelly/very cobbly sandy loam, brown to dark brown (7.5YR 4/3) moist; weak to moderate fine and medium subangular blocks to massive; loose to soft, very friable, slightly sticky, slightly plastic; few very fine roots; few very fine tubular pores; 20% gravel, mainly on the surface; effervescent; moderately alkaline (pH8.0-8.5); abrupt smooth boundary. This horizon has formed in the upper terrace fill deposit, and it is covered by a gravel pavement.

Bk1 3-18 cm. Light brown (7.5YR 6/3.5) gravelly/very cobbly sandy loam, brown (7.5YR 4.5/4) moist; weak to moderate fine and medium subangular blocks; soft, very friable, slightly sticky, slightly plastic; few to common very fine and few fine roots; few very fine tubular pores; 20% gravel; strongly effervescent; moderately alkaline (pH 8.0-8.5); clear smooth boundary. Contains disseminated carbonates in matrix and coatings on all sides of gravel.

2Bk2 18-40 cm. Light brown (7.5YR 6/4) extremely gravelly sandy loam, brown (7.5YR 5/4) moist; weak fine subangular blocks to massive; soft, very friable, slightly sticky, slightly plastic; 70% gravel and some cobbles; few to common very fine and fine roots; few tubular pores; strongly effervescent; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary. Contains few to common (5-10%) masses of carbonate and some finely disseminated carbonates; some consist of 6-10 mm cylindrical carbonate concentrations, possibly formed in old insect burrows. Contains disseminated carbonates in matrix and coatings on all sides of gravel.

2Btkm 40+ cm. Color of carbonate cement not described, but much lighter than above; illuvial clay is light brown (7.5YR 6/4), brown (7.5YR 5/4) moist; weakly cemented, massive, with some clay breaking out in blocks; many thick clay films on ped faces in clayey zones; 60-70% gravel; violently effervescent; moderately alkaline (pH 8.0-8.5). Contains few to common moderately hard masses of carbonate.

Profile Description 6: Grid interior

Geomorphic setting: Nearly level part of alluvial fan terrace, 1-2% slope
Agricultural setting: Within grid interior

A 0-3 cm. Pink to light brown (7.5YR 6.5/3.5) gravelly/very cobbly sandy loam, brown (7.5YR 4.5/3) moist; weak medium plates and weak fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; few very fine vesicular pores; 20% gravel; mildly alkaline (pH7.5); abrupt smooth boundary. This horizon has formed in the upper terrace fill deposit, and it is covered by a gravel pavement.

Bt 3-10 cm. Light brown (7.5YR 6/4) very gravelly/very cobbly sandy clay loam to loam, brown to dark brown (7.5YR 4/4) moist; weak fine to medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common thick clay bridges and colloidal stains on mineral grains; few to common very fine roots; few very fine tubular pores; 30% gravel and 10% cobbles; strongly effervescent; mildly alkaline (pH 7.5); clear smooth boundary.

2Bk 10-41+ cm. Light brown (7.5YR 6/4) extremely gravelly sandy loam, brown to strong brown (7.5YR 4.5/5) moist; weak fine subangular blocks; soft, very friable, slightly sticky, slightly plastic; few thin clay bridges; 40% gravel and 30% cobbles up to 12-15 cm in diameter; few to common very fine and fine roots, mainly in clusters; strongly effervescent; moderately alkaline (pH 8.0-8.5); abrupt smooth boundary. Contains disseminated carbonates in matrix, coatings on all sides of gravel, and some filaments.

Zuni Soil Study: Pedon Descriptions for Extensive Fields

Pescado, Cultivated 1

Classification: Nonacid, mixed, mesic Aridic Ustipsamment
Geomorphic setting: Footslope of alluvial fan, elevation 2070 m (6790 ft), 2% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated cornfield that is now fallow
Landuser: Master Eustace
Described by Jeff Homburg, Shawn Calavaza, Vanissa Laahte, Pete Natachu, and Lindsay Quam
Date: June 12/13, 1997

Ap 0-21 cm. Brown (10YR 4/3) sandy loam (moist); weak medium granules; soft, loose, nonsticky, nonplastic; common very fine, few fine, and few medium roots; common very fine tubular pores; 5% gravel; neutral (pH 7.0); clear wavy boundary.

C1 21-38 cm. Dark yellowish brown (10YR 4/4) loamy sand (moist); single grain; soft, loose, nonsticky, nonplastic; few very fine, fine, and medium roots; many very fine interstitial pores; 10% gravel; moderately alkaline (pH 8.0); clear smooth boundary.

C2 38-55 cm. Yellowish brown (10YR 5/4) loamy sand (moist); single grain; soft, loose, nonsticky, nonplastic; few very fine roots; many very fine interstitial pores; 35% gravel and 3% cobbles; moderately alkaline (pH 8.0); clear smooth boundary.

C3 55-60 cm. Yellowish brown (10YR 5/4) loamy sand (moist); single grain; soft, loose, nonsticky, nonplastic; few very fine roots; many very fine interstitial pores; 20% gravel; moderately alkaline (pH 8.0); clear smooth boundary.

2Btb 60-75 cm. Brown (10YR 4.5/3) loam to clay loam; weak to moderate coarse and very coarse subangular blocks; slightly hard, firm, sticky, plastic; many thin clay films on ped faces; few fine and very fine roots; many very fine and few fine tubular pores; moderately alkaline (pH 8.0); clear smooth boundary.

2Btkb 75-82+ cm. Brown (10YR 4/3) clay loam; weak to moderate coarse and very coarse subangular blocks; slightly hard, firm, sticky, plastic; many thin clay films on ped faces; few very fine roots; slightly to strongly effervescent, with some carbonate filaments; moderately alkaline (pH 8.0).

Auger: 82-100 cm, 2Btkb
110-230 cm, highly stratified alluvium, sandy loam and loamy sand

Pescado, Cultivated 2

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Footslope of alluvial fan, elevation 2060 m (6760 ft), 4% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated cornfield that is now fallow
Landuser: Sefferino Eriacho
Described by Jeff Homburg, Lindsay Quam, and Kerwin Owaleon
Date: June 19, 1997

Ap1 0-5 cm. Pale brown (10YR 6/3) sandy loam, brown (10YR 4/3) moist; weak to moderate fine and medium plates in upper 1 cm, moderate fine and medium granules; soft, very friable, slightly sticky, slightly plastic; common very fine, common fine, and few medium roots; common very fine interstitial pores; <1% gravel; slightly effervescent; neutral (pH 7.0); abrupt smooth boundary.

Ap2 5-17 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; weak to moderate fine and medium granules; soft, loose, nonsticky, nonplastic; common very fine and few fine roots; few very fine interstitial pores; slightly effervescent; neutral (pH 7.2); abrupt smooth boundary.

Bt1 17-62 cm. Brown (10YR 5/3) clay loam, brown to dark brown (10YR 4/3) moist; weak to moderate fine and medium subangular blocks; hard, firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few to common very fine and few fine roots; few to common very fine and few fine tubular pores; slightly effervescent; mildly alkaline (pH 7.8); gradual smooth boundary.

Bt2 62-75+ cm. Brown (10YR 5/3) clay loam, dark brown (10YR 3.5/3) moist; few to moderate fine and medium subangular blocks; hard, firm, sticky, plastic; common moderately thick clay films on ped faces and pores; few very fine roots; few very fine tubular pores; 10% gravel; slightly effervescent; moderately alkaline (pH 7.8).

Auger: 75-150 cm, Bt horizon
150-220 cm, BCtk horizon
220-230+ cm, C horizon

Pescado, Cultivated 3

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Colluvial footslope, elevation 2045 m (6710 ft), 6% slope

Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated cornfield that is now fallow
Landuser: Celestine Kanesta
Described by Jeff Homburg and Troy Lucio
Date: July 9, 1997

Ap1 0-7 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; moderate thin plates; soft to slightly hard, friable, nonsticky, nonplastic; many very fine roots; many very fine interstitial pores; 5% gravel; neutral (pH 6.8); clear smooth boundary.

Ap2 7-15 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; weak coarse subangular blocks; slightly hard, friable to firm, slightly sticky, slightly plastic; common very fine and few fine roots; many very fine tubular pores; 10% gravel; neutral (pH 7.1); gradual wavy boundary.

Bt1 15-52 cm. Brown to yellowish brown (10YR 5/3.5) clay loam, brown to dark yellowish brown (10YR 4/3.5) moist; moderate very coarse prisms parting to weak to moderate coarse and very coarse subangular blocks; very hard, very firm, slightly sticky, slightly plastic; common thin to moderately thick clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 15% gravel; mildly alkaline (pH 7.4); gradual smooth boundary.

Bt2 52-77+ cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; weak coarse subangular blocks; hard to very hard, firm to very firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; few very fine and fine roots; common very fine tubular pores; 7% gravel; slightly effervescent; mildly alkaline (pH 7.6).

Auger: 77-105 cm, Bt horizon, sandy loam, sandier with depth
105-145 cm, Btk horizon, sandy loam
145-190+ cm, C horizon, sandy loam with some cobbles
hit cobble and stopped at 190 cm

Pescado, Abandoned 1

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2054 m (6740 ft), 6% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned cornfield
Landuser: Hatti
Described by Jeff Homburg, Vanissa Lahty, and Troy Lucio
Date: July 8, 1997

Ap 0-11 cm. Grayish brown (10YR 5/2) loam, dark grayish brown (10YR 4/2) moist; moderate thin plates and common medium granules; slightly hard, firm, slightly sticky, slightly plastic; common very fine and few fine roots; many very fine interstitial pores; 5% gravel; neutral (pH 6.8); abrupt smooth boundary.

BA 11-20 cm. Brown (10YR 5/3) clay loam, very dark grayish brown to dark grayish brown (10YR 3.5/3) moist; strong fine and very fine granules and moderate to strong thin plates; hard, firm, sticky, plastic; common thin clay films on ped faces and pores; common very fine and few fine roots; common very fine and fine tubular pores; 3% gravel; neutral (pH 7.1); clear smooth boundary.

Bt 20-61 cm. Brown (10YR 5/3) clay loam, very dark grayish brown to dark grayish brown (10YR 3.5/3) moist; moderate very coarse prisms parting to weak very coarse subangular blocks; hard to very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine and few roots; common very fine and fine tubular pores; 3% gravel; neutral (pH 7.1); abrupt smooth boundary.

Btk 61-71+ cm. Pale brown (10YR 6/3) clay loam, brown (10YR 5/3) moist; weak coarse subangular blocks; very hard, firm to very firm, sticky, plastic; few thin clay films on ped faces and pores; few very fine roots; common very fine tubular pores; slightly effervescent; mildly alkaline (pH 7.8).

Auger: 71-130 cm, Btk horizon, clay loam
130-190 cm, C horizon, sandy loam
190-220+ cm, 2Btb horizon, loam to clay loam

Pescado, Abandoned 2

Classification: Coarse-loamy, mixed, mesic Fluventic Haplustept
Geomorphic setting: Alluvial fan, elevation 2054 m (6740 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned cornfield
Landuser: Rose Eustace
Described by Jeff Homburg, Troy Lucio, Kerwin Owaleon, and Lindsay Quam
Date: July 11, 1997

Ap 0-13 cm. Brown to pale brown (10YR 5.5/3) sandy loam, brown (10YR 4/3) moist; moderate thin plates; soft, very friable, slightly sticky, slightly plastic; many very fine and common fine roots; many very fine interstitial pores; 8% gravel; neutral (pH 6.7); abrupt wavy boundary.

Bt 13-33 cm. Yellowish brown (10YR 5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; weak coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine, few fine, and few medium roots; common very fine, few fine, and few medium tubular pores; 5% gravel; mildly alkaline (pH 7.7); abrupt wavy boundary.

C1 33-35 cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; single grain; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; common very fine tubular pores; mildly alkaline (pH 7.7); abrupt wavy boundary.

C2 35-39 cm. Yellowish brown (10YR 5/4) loamy sand, dark yellowish brown (10YR 4/4) moist; single grain; soft to slightly hard, friable to firm, nonsticky, nonplastic; common very fine and few fine roots; common very fine interstitial pores; 5% gravel; mildly alkaline (pH 7.8), abrupt wavy boundary.

C3 39-47 cm. Yellowish brown 10YR 5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; weak coarse subangular blocks; very hard, firm to very firm, sticky, plastic; few thin clay films on ped faces and pores; few very fine roots; common very fine tubular pores; 3% gravel; slightly effervescent; mildly alkaline (pH 7.8).

C4 47-52 cm. Yellowish brown (10YR 5/4) loamy sand, dark yellowish brown (10YR 4/4) moist; single grain; soft, friable, nonsticky, nonplastic; 15% gravel; common very fine and few fine roots; common very fine interstitial pores; mildly alkaline (pH 7.8), abrupt wavy boundary.

C5 52-57 cm. Yellowish brown (10YR 5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; single grain; soft to slightly hard, friable to firm, nonsticky, nonplastic; common very fine and few medium roots; common very fine interstitial pores; mildly alkaline (pH 7.8), abrupt wavy boundary.

2Btb 57-75+ cm. Grayish brown (10YR 5/2) clay loam, dark grayish brown (10YR 4/2) moist; weak to moderate coarse and very coarse subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine roots; common very fine tubular pores; moderately alkaline (pH 8.0).

Auger: 75-95 cm, Bt horizon, clay loam
95-145 cm, 2Btk horizon, clay loam
145-180 cm, 3Bt horizon, clay loam
180-210+ cm, sandy loam, sandy loam

Pescado, Abandoned 3

Classification: Fine-loamy, mixed, mesic Typic Haplustept
Geomorphic setting: Alluvial fan, elevation 2048 m (6720 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned cornfield
Landuser: F. Leekya
Described by Jeff Homburg and Troy Lucio
Date: July 10, 1997

Ap1 0-5 cm. Brown to pale brown (10YR 5.5/3) sandy loam, brown (10YR 4/3) moist; moderate to strong thin plates in upper 2 cm, weak to moderate fine granules; soft to slightly hard, firm, slightly sticky, slightly plastic; many very fine and common fine roots; many very fine interstitial pores; 8% gravel; slightly acid (pH 6.5); abrupt wavy boundary.

Ap2 5-14 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; weak medium and coarse subangular blocks and moderate thin plates; slightly hard to hard, firm, slightly sticky, slightly plastic; few thin clay films on pores; common very fine medium roots; many very fine tubular pores; 8% gravel; neutral (pH 6.8); clear wavy boundary.

Bt1 14-43 cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; weak very coarse prisms parting to weak to moderate coarse and very coarse subangular blocks; hard, very firm, sticky, plastic; common thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 10% gravel; mildly alkaline (pH 7.4).

Bt2 43-77+ cm. Brown (10YR 4.5/3) clay loam, dark brown (10YR 3.5/3) moist; moderate very coarse prisms parting to moderate very coarse subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 5% gravel; mildly alkaline (pH 7.6).

Auger: 77-95 cm, Bt2 horizon, clay loam
95-120 cm, 2C horizon, sandy loam
120+ cm, 3C loamy sand, too sandy to sample

Pescado, Uncultivated 1

Classification: Fine, mixed, mesic Aridic Paleustalf
Geomorphic setting: Alluvial fan, elevation 2073 m (6800 ft), 3% slope

Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field
Landuser: Judy Sanchez
Described by Jeff Homburg and Suzie Loadholt
Date: May 27-28, 1997

A 0-5 cm. Brown (10YR 5/3) fine sandy loam, brown (10YR 4/3) moist; weak medium plates, moderate fine and medium granules, and moderate medium subangular blocks; soft, friable, slightly sticky, slightly plastic; very few to few thin clay films on ped faces and pores; common very fine and fine roots; many very fine and fine tubular and vesicular pores; <2% gravel; neutral (pH 7.0); clear smooth boundary.

BAt 5-14 cm. Brown (10YR 5/3) sandy clay loam, brown (10YR 4/3) moist; weak fine and medium subangular blocks and weak fine granules; hard, friable to firm, sticky, plastic; common moderately thick clay films on ped faces and pores; common very fine and fine roots; common very fine and fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

Bt1 14-40 cm. Brown (10YR 4/3) fine sandy loam, dark brown (10YR 3/3) moist; strong medium prisms parting to moderate fine and medium subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few to common very fine and fine and few coarse roots; few very fine and fine tubular pores; <2% gravel; neutral (pH 7.2); gradual smooth boundary.

Bt2 40-50 cm. Brown (10YR 5/3) clay loam, dark brown (10YR 3.5/3) moist; moderate fine and medium subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few very fine roots; few very fine tubular pores; <2% gravel; audibly effervescent; moderately alkaline (pH 8.0); gradual smooth boundary.

Btk1 50-71 cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; moderate fine and medium subangular blocks; hard, firm, slightly sticky, slightly plastic; common thin to moderately thick clay films on ped faces and pores; few very fine roots; few very fine tubular pores; 2% gravel; strongly effervescent; moderately alkaline (pH 8.0); gradual smooth boundary.

Btk2 71-89 cm. Grayish brown to dark grayish brown (10YR 4.5/2) loam, very dark grayish brown (10YR 3/2) moist; moderate fine subangular blocks; hard, firm, sticky, plastic; few thin clay films on ped faces and pores; few very fine roots; few very fine and coarse tubular pores; <2% gravel; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

2ABtkb 89-118 cm. Grayish brown to brown (10YR 5/2.5) loam, dark brown (10YR 3.5/3) moist; weak fine and medium subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine roots; few very fine tubular pores; <2% gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

2ABtb1 118-142 cm. Brown (10YR 5/3 at the top grading to 10YR 5.5/3 at the bottom) sandy loam, brown to dark brown (10YR 4/3 at the top grading to 10YR 3.5/3 at the bottom) moist; weak to moderate fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine roots; few very fine tubular pores; <2% gravel; effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

2Btb 142-147+ cm. Brown to pale brown (10YR 5.5/3) clay loam, dark brown (10YR 3.5/3) moist; moderate fine and medium subangular blocks; very hard, very firm, sticky, plastic; few moderately thick clay films on ped faces and pores; few very fine roots; few very fine tubular pores; <2% gravel; neutral (pH 7.2).

Auger: 77-95 cm, Bt2 horizon, clay loam
95-120 cm, 2C horizon, sandy loam
120+ cm, 3C loamy sand, too sandy to sample

Pescado, Uncultivated 2

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2063 m (6770 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field, grazing area
Landuser: Rose Eustace
Described by Jon Sandor, Troy Lucio, and Lindsay Quam
Date: August 1-2, 1996

A 0-9 cm. Pale brown (10YR 6/3) fine sandy loam, brown (10YR 4/3) moist; weak to moderate thin and medium plates in upper 3 cm, moderate fine and medium granules, and moderate fine and medium subangular blocks parting to moderate fine and medium granules; soft and very friable in upper 3 cm, slightly hard, friable, slightly sticky, slightly plastic; common very fine and fine roots; common very fine and fine roots; 2-5% gravel; slightly acid (pH 6.5); abrupt smooth boundary.

BAt 9-28 cm. Pale brown to brown (10YR 5.5/3) clay loam, brown (10YR 4/3) moist. Moderate fine and medium subangular blocks and weak to moderate fine and medium granules; slightly hard to hard, friable to firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few to common very fine and fine and few medium roots; few to common very fine and fine and few medium tubular pores; 5% gravel; neutral (pH 7.8); clear smooth to slightly boundary.

Bt 28-69 cm. Brown to yellowish brown (10YR 5/3.5) clay loam, brown to dark yellowish brown (10YR 4/3.5) moist; moderate fine and medium prisms parting to moderate to strong fine and medium angular and subangular blocks; very hard, firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few to common very fine and few fine and medium roots; few to common very fine and few fine and medium tubular pores; 5-10% gravel; neutral (pH 7.2); abrupt to clear smooth boundary.

Btk 69-99+ cm. Pale brown to light yellowish brown (10YR 5.5/3.5) clay loam to silty clay, brown to yellowish brown (10YR 5/3.5) moist; moderate fine and medium subangular blocks; very hard, firm, sticky, plastic; common thin to moderately thick clay films on ped faces and pores; few very fine and fine roots; few very fine and fine tubular pores; 5% gravel; slightly to strongly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

2BCtk 99-137 cm. Light yellowish brown to yellowish brown (10YR 5.5/4) sandy loam to coarse sandy loam, yellowish brown (10YR 5/4) moist; few fine and medium subangular blocks; slightly hard to hard, friable, slightly sticky, slightly plastic; common thin to moderately thick clay bridges and clay films on pores; very few very fine and fine roots; few very fine and fine tubular pores; 10% gravel; slightly to strongly effervescent; mildly alkaline (pH 7.8); clear smooth boundary.

2C 137-150+ cm. Light yellowish brown to brownish yellow (10YR 6/5) loam sand, yellowish brown (10YR 5/5) moist; massive; soft, very friable, nonsticky, nonplastic; very few clay bridges and clay coatings on pores; few very fine roots; few very fine and coarse tubular pores; 10% gravel; very slightly effervescent; mildly alkaline (pH 7.7).

Auger: 150-180 cm, 2C horizon, loamy sand
180-200 cm, 3C? horizon, sandy loam
200-260 cm, 4Ab? horizon, loamy sand
260-300 cm, 4Btb? horizon, sandy clay loam, slightly calcareous is parts (not in matrix)
5-10% gravel and mostly audible to very slightly effervescent throughout.

Pescado, Uncultivated 3

Classification: Fine, mixed, mesic Aridic Paleustalf
Geomorphic setting: Alluvial fan, elevation 2036 m (6680 ft), 3.5% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Wilbur Haskie
Described by Jeff Homburg, Troy Lucio, and Lindsay Quam
Date: June 26, 1997

A 0-8 cm. Brown (10YR 5/3) fine sandy loam, brown (10YR 4/3) moist; moderate fine granules; soft, very friable, nonsticky, nonplastic; many very fine and few fine and medium roots; many very fine interstitial pores; 3% gravel; neutral (pH 7.3); abrupt wavy boundary.

AB 8-16 cm. Yellowish brown (10YR 5/4) fine sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; weak fine granules; slightly hard, friable to firm, nonsticky, nonplastic; common very fine and few fine roots; common very fine tubular pores; neutral (pH 7.0); abrupt smooth boundary.

BAt 16-22 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine roots; common very fine tubular pores; 5% gravel; strongly effervescent; mildly alkaline (pH 7.6); abrupt smooth boundary.

Bt 22-38 cm. Yellowish brown (10YR 5/4) clay loam to loam, dark yellowish brown (10YR 4/4) moist; common coarse and very coarse subangular blocks; slightly hard to hard, firm, slightly sticky, slightly plastic; common moderately thick clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 5% gravel; strongly effervescent; mildly alkaline (pH 7.6); abrupt smooth boundary.

2C1 38-41 cm. Yellowish brown (10YR 5/4) fine sandy loam, dark yellowish brown (10YR 4/4) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; common very fine roots; common very fine interstitial pores; strongly effervescent; mildly alkaline (pH 7.7); abrupt smooth boundary.

2C1 41-46 cm. Yellowish brown (10YR 5/4) loam, brown (10YR 4/3) moist; massive; slightly hard, friable to firm, slightly sticky, slightly plastic; few very fine roots; common very fine tubular pores; 3% gravel; strongly effervescent; mildly alkaline (pH 7.6); abrupt smooth boundary.

2C1 46-58 cm. Brown (10YR 5/3) loamy sand, brown (10YR 4/3) moist; single grain; soft, very friable, nonsticky, nonplastic; few very fine roots; few very fine tubular pores; strongly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

2C1 58-61 cm. Brown (10YR 5/3) fine sandy loam, brown (10YR 4/3) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; few very fine roots; few very fine tubular and common interstitial pores; strongly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Contains charcoal concentrations.

2C1 61-66 cm. Brown (10YR 5/3) fine sandy loam, brown (10YR 4/3) moist; massive; slightly hard, friable to firm, nonsticky, nonplastic; few very fine and fine roots; common very fine interstitial pores; strongly effervescent; 15-20% gravel; mildly alkaline (pH 7.8); abrupt smooth boundary.

3C2 66-74 cm. Brown (10YR 5/3) gravelly sandy loam, brown (10YR 4/3) moist; massive; soft to slightly hard, very friable, nonsticky, nonplastic; few very fine roots; common very fine interstitial pores; 15-20% gravel; strongly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

4C3 74-84+ cm. Light yellowish brown (10YR 6/4) fine sandy loam, yellowish brown (10YR 5/4) moist; massive; soft, friable, nonsticky, nonplastic; few very fine roots; common very fine interstitial pores; 8% gravel; strongly effervescent; mildly alkaline (pH 7.8).

Auger: 84-225 cm, 4C3 horizon, stratified sand to sandy loam throughout

Bear Canyon, Cultivated 1

Classification: Coarse-loamy, mixed, mesic Aridic Haplustept
Geomorphic setting: Footslope of alluvial fan, elevation 2078 m (6820 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated cornfield
Landuser: David Wyaco, Sr.
Described by Jeff Homburg and Jon Sandor
Date: July 17, 1997

Ap 0-33 cm. Pale brown to brown (10YR 5.5/3) fine sandy loam, brown (10YR 4/3) moist; weak fine granules and weak medium subangular blocks; soft to slightly hard, friable, slightly sticky, slightly plastic; common very fine and few fine roots; common very fine and fine tubular and interstitial pores; 5% gravel; strongly effervescent; mildly alkaline (pH 7.8); abrupt wavy boundary. Upper 0.5 cm contains very fine laminae and chunks of plant residue.

BA 33-58 cm. Pale brown to brown (10YR 5.5/5) fine sandy loam, brown (10YR 4/3) moist; weak medium subangular blocks; soft to slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; few very fine interstitial pores; 5% gravel; strongly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Lighter sand lens note from 41 to 43 cm.

Bw1 58-75 cm. Yellowish brown (10YR 5/4) loamy fine sand, dark yellowish brown (10YR 5/4) moist; massive; soft, very friable, nonsticky, nonplastic; common very fine and few fine roots; few very fine interstitial pores; 8% gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary. Fine gravel lenses noted from 64 to 66 cm.

2Bw2 75-87 cm. Brown to yellowish brown (10YR 5.5/4) loamy sand, yellowish brown to dark yellowish brown (10YR 4.5/4) moist; massive; soft, very friable, nonsticky, nonplastic; common very fine corn roots and few fine corn roots; few very fine interstitial pores; 30% gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

3Btb 87-108 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and few fine roots; few very fine tubular pores; 8% gravel; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary. Gravel lenses with 25% gravel noted from 92 to 99 cm.

3Btkb 108-118+ cm. Brown to yellowish brown (10YR 5.5/3.5) clay loam, brown to dark yellowish brown (10YR 4.5/3.5) moist; weak medium and coarse subangular blocks; slightly hard to hard, friable to firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and few fine roots; few very fine tubular pores; 5% gravel; very strongly effervescent, with carbonate filaments in rootlet pores; moderately alkaline (pH 8.0).

Auger: 118-200+ cm, calcareous sandy loam
Hit rock at 200 cm and stopped

Bear Canyon, Cultivated 4

Classification: Fine-loamy, mixed, mesic Aridic Haplustept
Geomorphic setting: Footslope of alluvial fan, elevation 2047 m (6715 ft), 2% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated field
Landuser: Calvert Martinez
Described by Jeff Homburg, Troy Lucio, and Kerwin Ontaleon
Date: July 23, 1997

Ap 0-15 cm. Grayish brown (10YR 5/2) loam, dark grayish brown (10YR 4/2) moist; weak to moderate medium subangular blocks, moderate fine granules; slightly hard, friable, slightly sticky, slightly plastic; common very fine and fine roots; many very fine interstitial pores; 5% gravel; neutral (pH 6.6); abrupt wavy boundary.

BAt 15-25 cm. Brown (10YR 5/3) sandy clay loam, brown (10YR 4/3) moist; weak medium subangular blocks; slightly hard, friable to firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and few fine roots; common very fine and few fine tubular pores; 10% gravel; mildly alkaline (pH 7.4); abrupt wavy boundary.

Bt 25-36 cm. Yellowish brown (10YR 5/4) loamy fine sand, dark yellowish brown (10YR 4/4) moist; weak to moderate medium and coarse subangular blocks; slightly hard, friable, nonsticky, nonplastic; few thin clay films on ped faces and pores and few bridges; common very fine and few fine roots; common very fine and few fine interstitial pores; 5% gravel; mildly alkaline (pH 7.8); abrupt smooth boundary.

2Btkb1 36-51 cm. Brown (10YR 5/3) loam, brown to dark brown (10YR 3.5/3) moist; weak to moderate medium and coarse subangular blocks; hard to very hard, very firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and few fine roots; common very fine tubular pores; 3% gravel; strongly effervescent; mildly alkaline (pH 7.8); clear smooth boundary.

2Btkb2 51-75+ cm. Brown to yellowish brown (10YR 5.5/4) loam to clay loam, dark brown (10YR 3/3) moist; moderate medium and coarse subangular blocks; hard to very hard, very firm, sticky, plastic; common thin to moderately thick clay films on ped faces and pores; common very fine and few fine roots; common very fine tubular pores; 3% gravel; strongly effervescent; mildly alkaline (pH 7.8).

Auger: 75-90 cm, 2Btb2 horizon continues
Hit cobbly layer (or bedrock) in two augers at 90 cm and stopped.

Bear Canyon, Cultivated 5

Classification: Coarse-loamy, mixed, mesic Aridic Haplustept
Geomorphic setting: Footslope of alluvial fan, elevation 2028 m (6655 ft), 2% slope

Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated field, now fallow and covered by many grasses
Landuser: Edward Beyuka
Described by Jeff Homburg, Troy Lucio, and Lindsay Quam
Date: June 4, 1998

Ap 0-17 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; moderate thin plates in upper 2 cm, weak fine granules; slightly hard, firm, slightly sticky, slightly plastic; many very fine and common fine roots; many very fine and common fine tubular pores; 1% gravel; slightly effervescent; mildly alkaline (pH 7.8); abrupt wavy boundary.

BAt 17-31 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; weak to moderate fine subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; many very fine and common fine roots; many very fine and few fine tubular and few coarse interstitial pores; <1% gravel; mildly alkaline (pH 7.8); clear smooth boundary.

C 31-44 cm. Yellowish brown (10YR 5/4) loamy sand, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; soft, very friable, nonsticky, nonplastic; many very fine and common fine roots; many very fine and common fine interstitial pores; <1% gravel; mildly alkaline (pH 7.8); clear smooth boundary.

2Btb 44-73 cm. Dark yellowish brown (10YR 4/4) sandy loam, dark brown to dark yellowish brown (10YR 3.5/4) moist; moderate medium subangular blocks; soft, friable, nonsticky, nonplastic; few thin clay films on ped faces; many very fine and common fine roots; many very fine and common fine tubular pores; slightly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

3Btb 73-90+ cm. Very dark grayish brown to dark brown (10YR 3/2.5) clay loam, very dark brown (10YR 2/2) moist; moderate to strong medium subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; many very fine and few fine roots; common very fine and few fine tubular pores; mildly alkaline (pH 7.8).

Auger: 90-105 cm, 3Btb horizon, clay loam
105-185 cm, 3BCtb horizon, loam
185-210 cm, 4Btkb horizon, clay loam, slightly effervescent
210-225 cm, 5Btb horizon, clay loam, audibly effervescent

Bear Canyon, Abandoned 1

Classification: Fine-loamy, mixed, mesic Fluventic Haplustept
Geomorphic setting: Alluvial fan, elevation 2079 m (6820 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned cornfield
Landuser: Victor Niiha
Described by Jeff Homburg, Troy Lucio, and Lindsay Quam
Date: June 20, 1997

Ap 0-8 cm. Brown (10YR 5/3) and brownish yellow (10YR 6/6) silt loam, brown (10YR 4/3) and yellowish brown moist; weak very thin and thin plates in upper 3 cm, moderate very fine and fine granules; slightly hard, friable, sticky, plastic; very few thin clay films on ped faces and pores; many very fine, common fine, and many medium and coarse roots; many very fine tubular and vesicular pores; 4% gravel; mildly alkaline (pH 7.8); abrupt wavy boundary.

Bt1 8-23 cm. Pale brown to brown (10YR 5.5/3) fine sandy loam, brown (10YR 4/3) moist; weak to moderate coarse and very coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and few fine and coarse roots; common very fine tubular pores; 5% gravel; neutral (pH 7.0); clear smooth boundary.

Bt2 23-33 cm. Brown to yellowish brown (10YR 5/3.5) sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; weak coarse and very coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and few coarse roots; few very fine tubular pores; 5% gravel; mildly alkaline (pH 7.5); abrupt smooth boundary.

2C1 33-50 cm. Yellowish brown (10YR 5/4) sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; common very fine tubular pores; 5-8% gravel; mildly alkaline (pH 7.8); abrupt smooth boundary.

2C2 50-56 cm. Yellowish brown to lightly yellowish brown (10YR 5.5/4) loamy sand, dark yellowish brown (10YR 4/4) moist; massive; loose, very friable, nonsticky, nonplastic; common very fine roots; common very fine tubular pores; neutral (pH 7.2); abrupt smooth boundary.

4C3 56-66 cm. Dark gray (10YR 4/1) and brown (10YR 5/3) loam, very dark gray (10YR 3/1) and brown (10YR 4/3) moist; massive; slightly hard, firm, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; mildly alkaline (pH 7.6); abrupt smooth boundary.

5C4 66-77 cm. Dark gray (10YR 4/1) and brown (10YR 5/3) sandy loam, very dark gray (10YR 3/1) and brown (10YR 4/3) moist; massive; soft, friable, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; mildly alkaline (pH 7.8); abrupt smooth boundary.

6C5 77-82+ cm. Dark grayish brown (10YR 4/2) silt loam, dark brown (10YR 3/2) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; common very fine and few medium roots; common very fine tubular pores; audibly effervescent; mildly alkaline (pH 7.8).

Auger: 82-120 cm, 6C5 horizon, silt loam to sandy loam
120-200 cm, 7C6 horizon, sandy loam
200-220+ cm, Ck horizon, loam

Bear Canyon, Abandoned 2

Classification: Fine-loamy, mixed, mesic Aridic Haplustalfs
Geomorphic setting: Alluvial fan, elevation 2152 m (7060 ft), 4-5% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned corn/bean field
Landuser: Ira Bowannie
Described by Jeff Homburg, Jon Sandor, Pete Natachu, Troy Lucio, Kerwin Owaleon, and Lindsay Quam
Date: July 16, 1997

Ap 0-6 cm. Brown to grayish brown to light olive brown (2.5Y-10YR 5/3) loam, very dark grayish brown-olive brown to brown-dark brown (2.5Y-10YR 3.5/3) moist; moderate medium plates parting to moderate fine granules; soft, very friable, slightly sticky, slightly plastic; common very fine and few fine roots; few very fine vesicular pores; 5% gravel; audibly effervescent; mildly alkaline (pH 7.5); abrupt smooth boundary.

Ap/C 6-16 cm. Pale brown to lightly yellowish brown (10YR 6/3.5) sandy loam, brown (10YR 4/3) moist; weak fine subangular blocks in pockets; slightly hard, friable, nonsticky, nonplastic; common very fine and few fine roots; common very fine tubular pores; 5% gravel; slightly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Contains 2-3 mm thick laminations.

Bk 16-38 cm. Yellowish brown (10YR 5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, nonsticky, nonplastic; common very fine roots; few very fine tubular pores; 10% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

Bt1 38-48 cm. Light brownish gray-light yellowish brown to pale brown (2.5Y-10YR 6/3) loam, dark grayish brown-olive brown to brown (2.5Y-10YR 4/3) moist; weak to moderate medium subangular blocks; hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine roots; few very fine tubular pores; 5% gravel; moderately alkaline (pH 8.0); clear smooth boundary.

Bt2 48-83 cm. Pale brown to brown (10YR 5.5/3) loam, brown to dark brown (10YR 3.5/3) moist; weak medium prisms parting to weak to moderate medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; common to many thin clay films on ped faces and pores; few very fine roots; common very fine tubular pores; moderately alkaline (pH 8.0); gradual smooth boundary. Contains some vertical cracks.

Btk 83-90 cm. Pale brown (10YR 6/3) loam, brown (10YR 4.5/3) moist; slightly hard, friable, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; few very fine roots; common very fine tubular pores; slightly effervescent; moderately alkaline (pH 7.8).

Auger: 90-105 cm, weak Btk horizon, sandy loam, strongly effervescent
105-165 cm, 2Btk horizon, clay loam
200-220+ cm, 2BCtk horizon, loam, slightly effervescent

Bear Canyon, Abandoned 3

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2035 m (6675 ft), 2.5% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned cornfield
Landuser: Edward Beyuka
Described by Jeff Homburg, Troy Lucio, and Lindsay Quam
Date: July 16, 1997

Ap 0-14 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; weak to moderate very fine and fine granules; slightly hard, firm, slightly sticky, slightly plastic; many very fine and common few fine roots; many very fine and common fine tubular pores; 3% gravel; moderately alkaline (pH 8.0); abrupt wavy boundary.

BAt 14-28 cm. Brown (10YR 4/3) loam, dark brown (10YR 3/3) moist; moderate fine and medium subangular; hard, firm, slightly sticky, slightly plastic; many very fine and common fine roots; many very fine and common fine tubular pores; 2% gravel; audibly effervescent; moderately alkaline (pH 8.0); clear wavy boundary.

Bt1 28-40 cm. Brown (10YR 4/3) sandy clay loam, dark brown (10YR 3/3) moist; moderate fine and medium subangular blocks; hard, firm, slightly sticky, slightly plastic; common very fine and few fine roots; common very fine and few fine tubular pores; 2% gravel; audibly effervescent; moderately alkaline (pH 8.0); gradual smooth boundary.

Bt2 40-60 cm. Brown (10YR 4/3) loam, dark brown to very dark brown (10YR 3/2.5) moist; moderate fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; many thin clay films on ped faces and pores; common very fine and few fine roots; common very fine and few fine tubular pores; slightly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

BCt 60-81 cm. Brown to dark yellowish brown (10YR 4/3.5) loam, dark brown (10YR 3/3) moist; moderate fine medium and fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic, few thin clay films on ped faces and pores; common very fine and few fine roots; common very fine and few fine tubular pores; 1% gravel; slightly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

CB 81-90+ cm. Brown (10YR 5/3) sandy loam, brown to dark brown (10YR 3.5/3) moist; weak fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; very few clay films on ped faces; few very fine and fine roots; few very fine and fine tubular pores; slightly effervescent; moderately alkaline (pH 8.0).

Bear Canyon, Abandoned 4

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Footslope of alluvial fan, elevation 2067 m (6780 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated field
Landuser: Wilmer Quandelacy
Described by Jeff Homburg and Troy Lucio
Date: June 20, 1997

Ap 0-13 cm. Brown (10YR 5/3) fine sandy loam, brown (10YR 4/3) moist; weak thin plates in upper 1 cm, weak medium and coarse subangular blocks; soft, friable, nonsticky, nonplastic; common very fine and few fine roots; many very fine tubular and many very fine vesicular pores; 8% gravel; slightly acid (pH 6.5); abrupt wavy boundary.

BAt 13-29 cm. Grayish brown to light olive brown (2.5Y 5/3) fine sandy loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak medium and very coarse subangular blocks; slightly hard, friable to firm, nonsticky, nonplastic; few thin clay films on ped faces and pores; common very fine and few coarse roots; common very fine and few fine tubular pores; 10% gravel; neutral (pH 6.8); gradual wavy boundary.

Bt1 29-60 cm. Grayish brown to light olive brown (2.5Y 5/3) loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate very coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine, few medium and coarse roots; common very fine and few fine tubular pores; 10% gravel; neutral (pH 7.3); clear smooth boundary.

Bt2 60-69 cm. Grayish brown to light olive brown (2.5Y 5/3) loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate very coarse subangular blocks; slightly hard, firm, sticky, plastic; moderate thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 10% gravel; mildly alkaline (pH 7.5); abrupt smooth boundary.

Bt2 69-80 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) sandy loam, grayish brown to light olive brown (2.5Y 5/3) moist; weak medium and coarse subangular blocks; soft to slightly hard, friable to firm, nonsticky, nonplastic; few thin clay bridges; few very fine roots; common very fine tubular pores; 5% gravel; mildly alkaline (pH 7.8).

Auger: 80-120 cm, BCt horizon, sandy loam, no effervescence
120-220 cm, C, loamy fine sand, no effervescence

Bear Canyon, Uncultivated 1

Classification: Fine-loamy, mixed, mesic Fluventic Haplustept
Geomorphic setting: Alluvial fan, elevation 2094 m (6870 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Fred Weekoty
Described by Jeff Homburg and Suzie Loadholt
Date: June 20, 1997

A 0-5 cm. Brown (10YR 5/3) loam, dark grayish brown (10YR 4/2) moist; weak thin plates in upper 0.5 cm, weak to moderate fine and medium granules; soft, very friable to friable, slightly sticky, slightly plastic; common very fine and fine roots; many very fine vesicular pores; <5% gravel; neutral (pH 7.0); abrupt smooth boundary.

BAt 5-12 cm. Brown (10YR 5/3) sandy loam, dark grayish brown (10YR 4/2) moist; weak fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few coarse roots; common very fine and fine tubular and few very fine vesicular pores; <5% gravel; mildly alkaline (pH 7.5); clear smooth boundary.

Bt1 12-39 cm. Grayish brown to brown (10YR 5/2.5) sandy clay loam to loam, dark to very dark grayish brown (10YR 3.5/2) moist; moderate medium prisms parting to weak fine and medium subangular blocks; hard, friable to firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and fine roots; many very fine and few fine tubular pores; <5% gravel; slightly acidic (pH 6.5); clear smooth boundary.

Bt2 39-56 cm. Brown (10YR 5/3) loam, dark brown (10YR 3/3) moist; moderate fine and medium prisms parting to weak fine and medium subangular blocks; very hard, very firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few to common fine roots; many fine and few fine tubular pores; 10% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

2C1 56-80 cm. Yellowish brown (10YR 5/4) loamy sand, brown to dark yellowish brown (10YR 4/3.5) moist; massive; soft, very friable, nonsticky, nonplastic; few fine roots; few very fine tubular pores; 5-10% gravel and one 15 cm cobble; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains very few 1 mm laminations.

3C2 80-87 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; hard, friable to firm, slightly sticky, slightly plastic; few very fine and fine roots; common very fine and few fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains common 1 mm laminations and charcoal flecks.

4C3 87-107 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; slightly hard, very friable, slightly sticky, slightly plastic; few medium roots; common very fine interstitial pores; 5% gravel;

moderately alkaline (pH 8.0); abrupt smooth boundary. Contains many 1-3 mm laminations, and a charcoal lens in the lower part.

88-100 cm. Gravelly lens in southwest corner of pit. Yellowish brown (10YR 5/4) gravelly loamy sand, dark yellowish brown (10YR 4/4) moist; single grain; loose, very friable, nonsticky, nonplastic; many fine interstitial pores; 20% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

4C4 107-123 cm. Pale brown (10YR 6/3) fine sandy loam, brown (10YR 5/3) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine and medium roots; common very fine interstitial pores; 10-15% gravel; moderately alkaline (pH 8.0); clear smooth boundary. Highly laminated (1 mm) and contains many charcoal flecks.

4C5 123-139+ cm. Pale brown (10YR 6/3) fine sandy loam; brown (10YR 5/3) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; few fine roots; common very fine interstitial pores; 5% gravel; moderately alkaline (pH 8.0). Highly laminated (1 mm) and contains many charcoal flecks.

Auger: 139-180 cm, 4C5 horizon continues, fine loamy sand
180-245 cm, 5C6 horizon, gravelly fine loamy sand
Hit rock at 245 cm and stopped.

Bear Canyon, Uncultivated 2

Classification: Coarse-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2045 m (6710 ft), 4% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Wilmer Quandelacy
Described by Jeff Homburg, Kerwin Owaleon, and Lindsay Quam
Date: June 17, 1997

A 0-14 cm. Grayish brown to dark grayish brown (10YR 4.5/2) sandy loam, brown (10YR 4/3) moist; weak fine granules; soft, very friable, slightly sticky, slightly plastic; common very fine and few fine roots; common very fine interstitial pores; 5% gravel; slightly acidic (pH 6.5); gradual smooth boundary.

BAt 14-45 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; weak fine and medium subangular blocks to massive; soft, friable, nonsticky, nonplastic; very few thin clay bridges; common very fine roots; many very fine interstitial pores; 5% gravel; slightly acidic (pH 6.5); clear smooth boundary.

Bt 45-56 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; massive to very weak fine and medium subangular blocks; soft, friable, slightly sticky, slightly plastic; few thin clay bridges; few very fine roots; many very fine interstitial pores; 8% gravel; neutral (pH 7.0); abrupt wavy boundary.

2C1 56-60 cm. Pale brown (10YR 6/3) loam, brown (10YR 4/3) moist; massive; soft, friable, slightly sticky, slightly plastic; few very fine roots; few very fine tubular pores; moderately alkaline (pH 8.2); abrupt wavy boundary. Highly laminated (1 mm) and contains abundant charcoal flecks.

3C2 60-86 cm. Pale brown (10YR 6/3) loamy sand, yellowish brown to dark yellowish brown (10YR 4.5/4) moist; single grain; loose, loose, nonsticky, nonplastic; few fine roots; common very fine interstitial pores; 10% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

4C3 86-93+ cm. Brown (10YR 5/3) gravelly loamy sand, yellowish brown to dark yellowish brown (10YR 4.5/4) moist; single grain; loose, loose, nonsticky, nonplastic; few very fine roots; few very fine interstitial pores; 35% gravel; moderately alkaline (pH 8.0).

Auger: 93-130 cm, 4C3 horizon continues, gravelly loamy sand
130-160 cm, 5Ab horizon, loam, continues many charcoal flecks
160-220 cm, 5C horizon, highly stratified sandy alluvium

Bear Canyon, Uncultivated 3

Classification: Coarse-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2047 m (6715 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: David Wyaco, Sr.
Described by Jon Sandor, Jeff Homburg, and Troy Lucio
Date: July 17, 1997

A 0-14 cm. Pale brown (10YR 6/3) loam, brown (10YR 4/3) moist; weak medium plates and weak fine and medium granules in upper 4 cm, weak fine and medium granules and weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; 10% gravel; neutral (pH 7.0); clear smooth boundary.

Bw 14-34 cm. Pale brown to brown (10YR 5.5/3) loam to clay loam, brown (10YR 4/3) moist; weak to moderate medium subangular blocks; slightly hard, friable, slightly sticky to sticky, slightly plastic to plastic; very few to few thin clay bridges and clay films on pores; common very fine roots; few very fine tubular pores; 8% gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains some pockets of sandy loam.

C 34-43 cm. Pale brown to light yellowish brown (10YR 6/3.5) sandy loam, yellowish brown (10YR 4/3) moist; massive with some lens of weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

43-51 cm. Brown (10YR 5/3) loam from 43 to 47 cm and brown (10YR 5/3) sandy loam from 47 to 51 cm, brown (10YR 4.5/3) moist; massive; slightly hard, friable, slightly sticky to nonsticky, slightly plastic to nonplastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly effervescent; moderately alkaline; (pH 8.0); abrupt smooth boundary. Contains some charcoal flecks.

51-58 cm. Brown (10YR 5/3) loam, brown (10YR 4.5/3) moist; massive with some lens of weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

58-62 cm. Pale brown to light yellowish brown (10YR 6/3.5) sandy loam, yellowish brown (10YR 5/4) moist; massive with some lens of weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

62-71 cm. Contains three light bands of pale brown to light yellowish brown (10YR 6/3.5) sandy loam, yellowish brown (10YR 4/3) moist, and three dark bands of brown (10YR 5/3) loam, brown

(10YR 4.5/3) moist; massive with some lens of weak medium subangular blocks; slightly hard, friable, slightly sticky to non sticky, slightly plastic to nonplastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly alkaline; moderately alkaline (pH 8.0); abrupt smooth boundary

71-79 cm. Brown (10YR 5/3) loam from 71 to 75 cm, brown (10YR 4.5/3) moist, and pale brown to light yellowish brown (10YR 6/3.5) sandy loam from 75 to 79 cm, yellowish brown (10YR 5/4) moist; massive with some lens of weak medium subangular blocks; slightly hard, friable, slightly sticky to nonsticky, slightly plastic to nonplastic; common very fine roots; few very fine tubular pores; 5% gravel (in lens and pockets); strongly alkaline; moderately alkaline (pH 8.0); abrupt smooth boundary

2Btb 79-92+ cm. Pale brown to brown (10YR 5.5/3) loam, brown (10YR 4/3) moist; weak medium and coarse subangular blocks; hard, friable, slightly sticky, slightly plastic; few thin clay bridges and clay films on pores; common very fine roots; 10% gravel, with a thin band of 50% gravel from 79 to 80 cm; few very fine tubular pores; slightly to strongly effervescent; moderately alkaline (pH 8.0).

Auger: 92-110 cm, 2Btb horizon continues, loam
110-195+ cm, 2C horizon, loam to sandy loam

Bear Canyon, Uncultivated 4
Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Footslope of alluvial fan, elevation 2048 m (6720 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within field originally thought to have been cultivated, based on presence of stone alignments and initial reports, but later found to be uncultivated. Rock alignments were built simply as erosion control features in a field using for grazing, according to Andy Laahte.
Landuser: Chopito
Described by Jeff Homburg and Lindsay Quam
Date: June 16, 1997

A1 0-7 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; massive; loose, very friable, nonsticky, nonplastic; common very fine roots; many very fine interstitial pores; <5% gravel; slightly acid (pH 6.5); clear wavy boundary. Represents recent alluvial deposit with little soil development.

A2 7-16 cm. Grayish brown (10YR 5/2) fine sandy clay loam to clay loam, dark to very dark grayish brown (10YR 3.5/2) moist; weak coarse subangular blocks; soft, friable, slightly sticky, slightly plastic; very few thin clay films on ped faces; common very fine roots; common very fine tubular pores; 5-10% gravel; slightly acid (pH 6.5); abrupt wavy boundary.

BAt 16-31 cm. Grayish brown (10YR 5/2) sandy clay loam to clay loam, very dark grayish brown (10YR 3/2) moist; weak to moderate very coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 5-10% gravel; neutral (pH 7.0); gradual smooth boundary.

Bt1 31-54 cm. Grayish brown (10YR 5/2) sand clay loam, dark grayish brown (10YR 4/2) moist; weak to moderate coarse and very coarse subangular blocks; slightly hard, firm, sticky, plastic; many thin clay films on ped faces and pores; few very fine roots; common very fine tubular pores; 5-10% gravel; moderately alkaline (pH 8.0); gradual smooth boundary.

Bt2 54-80 cm. Grayish brown (10YR 5/2) clay loam, dark grayish brown (10YR 4/2) moist; weak to moderate coarse and very coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; many thin clay films on ped faces and pores; few very fine roots; few very fine tubular pores; 5-10% gravel; moderately alkaline (pH 8.0).

Auger: 80-125 cm, BCt horizon, sandy loam, some clay bridges
125-190 cm, BCk, loam with carbonate threads and weak subangular structure
190-225+ cm, C horizon, loam sand

Nutria, Cultivated 1

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Colluvial footslope below Mexican Hill, elevation 2091 m (6860 ft), 5% slope
Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated, now fallow
Landuser: Dennis Peynetsa
Described by Jeff Homburg and Nick Martin
Date: July 24, 1997

Ap 0-16 cm. Brown to yellowish brown (2.5Y-10YR 5/3.5) sandy loam, brown to dark yellowish brown (2.5Y-10YR 4/3.5) moist; weak to moderate fine granules and weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine and few fine roots; common very fine interstitial pores; 1% gravel; mildly alkaline (pH 7.8); abrupt wavy boundary.

BAt 16-30 cm. Yellowish brown (2.5Y-10YR 5/4) sandy loam, dark yellowish brown (2.5Y-10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable to firm, nonsticky, nonplastic; very few to few thin clay films on ped faces and pores; common very fine and few fine roots; common very fine and few fine tubular pores; 3% gravel; audibly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

2Btb1 30-57 cm. Brown (10YR 4.5/3) loam, dark brown (10YR 3/3) moist; weak to moderate medium and coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 2% gravel; strongly effervescent; moderately alkaline (pH 8.0); gradual smooth boundary.

2Bb2 57-70 cm. Grayish brown to brown (10YR 5/2.5) loam, very dark grayish brown to dark brown (10YR 3/2.5) moist; moderately medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; common thin to moderately thick clay films on ped faces and pores; common very fine roots; common very fine interstitial pores; 1% gravel; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

2Btb3 70-91 cm. Grayish brown to brown (10YR 5/2.5) clay loam, very dark grayish brown to dark brown (10YR 3/2.5) moist; moderate medium and coarse subangular blocks; very hard, firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few very fine roots; common very fine tubular pores; 1% gravel; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

2Btkb 91-101+ cm. Brown (10YR 4.5/3) clay loam, brown to dark brown (10YR 3.5/3) moist; weak to moderate medium and coarse subangular blocks; hard, firm, sticky, plastic; common to many moderately thick clay films on ped faces and pores; few very fine roots; few very fine tubular pores; 1% gravel; strongly effervescent; moderately alkaline (pH 8.0).

Auger: 101-125 cm, 2Btkb, clay loam
125-150 cm, 2Bkb, clay loam
150-185 cm, 2BCkb, sandy clay loam

185-230 cm, 2CBkb, sandy loam
230-240+ cm, 2Ckb, sandy loam

Nutria, Cultivated 2
Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2070 m (6790 ft), 5% slope
Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated corn and squash field
Landuser: Wilmer Quandelacy
Described by Jeff Homburg and Troy Lucio
Date: June 23, 1997

Ap 0-18 cm. Grayish brown to light olive brown (2.5Y 5/3) loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate fine and medium granules and weak to moderate medium and coarse subangular blocks; slightly hard, friable to firm, slightly sticky, slightly plastic; common very fine and few fine and few coarse roots; many very fine vesicular and interstitial pores; 3% gravel; mildly alkaline (pH 7.5); abrupt wavy boundary.

Bt 18-37 cm. Light brownish gray to light brownish yellow (2.5Y 6/3) clay loam, grayish brown to light olive brown (2.5Y 5/3) moist; weak to moderate medium and coarse subangular blocks; hard, firm to very firm, sticky, plastic; common thin clay films on ped faces and pores; common very fine and few medium roots; common very fine tubular pores; 3% gravel; neutral (pH 7.0); abrupt smooth boundary.

2C1 37-47 cm. Light olive brown (2.5Y 5/4) fine sandy loam, olive brown (2.5Y 4/4) moist; massive; slightly hard, firm, slightly sticky, slightly plastic; common very fine and few medium roots; common very fine tubular pores; 3% gravel; mildly alkaline (pH 7.0); abrupt wavy boundary. Contains many charcoal flecks.

3BCtkb 47-77 cm. Grayish brown to light olive brown (2.5Y 5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak medium and coarse subangular blocks to massive; slightly hard to hard, firm to very firm, sticky, plastic; few thin clay films on ped faces and pores; common very fine and few fine roots; common very fine tubular pores; 3% gravel; slightly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Contains some fine laminations.

4C2 77-82 cm. Light yellowish brown (2.5Y 6/4) fine sandy loam, light olive brown (2.5Y 5/4) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; few very fine roots; few very fine interstitial pores; 3% gravel; mildly alkaline (pH 7.4).

Auger: 82-90 cm, 4C2 continues, sandy loam
90-130 cm, 5Bkb, loam to clay loam
130-220+ cm, 5C, highly stratified alluvium/colluvium

Nutria, Cultivated 3
Classification: Fine-loamy, mixed Aridic Haplustalf
Geomorphic setting: Colluvial footslope below Mexican Hill, elevation 2085 m (6840 ft), 8% slope
Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within cultivated field, now follow
Landuser: Chauncey Simplicio
Described by Jeff Homburg, Jon Sandor, Vanissa Laahty, Troy Lucio, and Kerwin Ontaleon
Date: July 22, 1997

Ap 0-19 cm. Brown (10YR 4/3) sandy loam, dark brown (10YR 3/3) moist; weak fine granules and weak medium subangular blocks; slightly hard, friable, slightly sticky to nonsticky, slightly plastic to nonplastic; common very fine and few fine coarse roots; many very fine interstitial pores; 3% gravel; slightly effervescent from 2-19 cm; moderately alkaline (pH 8.0); abrupt wavy boundary.

BAt 19-28 cm. Dark brown to very dark brown (10YR 4/3) loam, dark brown (10YR 3/3) moist; weak to moderate medium subangular blocks; hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; 2% gravel; slightly effervescent; moderately (pH 8.0); clear smooth boundary. Contains few fine carbonate filaments.

Btk1 28-58 cm. Brown (10YR 4/3) clay loam, dark brown (10YR 3/3) moist; moderate medium and coarse subangular blocks; very hard, very firm, sticky, plastic; common thin to moderately thick clay films on ped faces and pores; common very fine and few medium roots; common very fine and few coarse tubular pores; 5% gravel; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary. Contains common fine carbonate filaments and coatings; cobbles have coatings on all sides, but thickest on the bottom.

Btk2 58-78 cm. Yellowish brown (10YR 5/4) sandy clay loam, brown (10YR 4/3) moist; moderate medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and few medium roots; few very fine and coarse tubular pores; 3% gravel; slightly effervescent; moderately alkaline (pH 8.0); clear smooth boundary. Contains few fine carbonate filaments.

BCtk 78-88 cm. Pale brown (10YR 6/3) sandy loam, brown (10YR 4/3) moist; weak to moderate medium subangular blocks; hard, firm, slightly sticky, slightly plastic; few very fine and medium roots; few very fine tubular pores; 3% gravel; strongly effervescent; moderately alkaline (pH 8.0). Contains very few fine carbonate filaments.

Auger: 88-120 cm, BCtk continues, sandy loam
120-150 cm, BCtk, loam
150-240+ cm, BCk-CBk, sandy loam, very few clay films

Nutria, Abandoned 1

Classification: Fine, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2097 m (6880 ft), 2% slope
Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned field
Landuser: Rex Chimoni
Described by Jeff Homburg, Troy Lucio, and Lindsay Quam
Date: July 14, 1997

Ap1 0-5 cm. Grayish brown to light olive brown (2.5Y 5/3) loam, dark grayish brown to olive brown (2.5Y 4/3) moist; moderate thin plates (0 to 0.7 cm) and moderate very fine granules; soft to slightly hard, friable, slightly sticky, slightly plastic; common very fine and few medium roots; many very fine vesicular pores; 3% gravel; neutral (pH 6.7); abrupt smooth boundary.

Ap2 5-16 cm. Grayish brown to light olive brown (2.5Y 5/3) loam, dark grayish brown to olive brown (2.5Y 4/2.5) moist; weak medium subangular blocks; slightly hard, friable, sticky, plastic; few thin clay films on ped faces and pores; common very fine and few fine and medium roots; common very fine and few fine tubular pores; 2% gravel; mildly alkaline (pH 7.8); abrupt wavy boundary. Contains very few fine carbonate filaments.

Bt 16-38 cm. Grayish brown to light yellowish brown (2.5Y 5.5/3) clay loam, dark grayish brown to olive brown (2.5Y 3/3) moist; moderate coarse and very coarse subangular blocks; hard, firm, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine and few fine roots; common very fine and few coarse tubular pores; <1% gravel; audibly effervescent; neutral (pH 7.2); gradual smooth boundary.

Btk1 38-62 cm. Grayish brown to olive brown (2.5Y 5/3) clay loam, dark grayish brown (2.5Y 4/2) moist; weak to moderate medium and coarse subangular blocks; very hard, very firm, sticky, plastic; common thin clay films on ped faces and pores; common very few and few fine roots; few very fine tubular pores; 1% gravel; slightly effervescent; mildly alkaline (pH 7.7); clear smooth boundary. Contains very few fine carbonate filaments.

Btk2 62-75 cm. Grayish brown to light grayish brown (2.5Y 5.5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/2.5) moist; weak to moderate medium and coarse subangular blocks; hard, firm, sticky, plastic; common thin clay films on ped faces and pores; few very fine; few very fine tubular pores; 4% gravel; slightly effervescent; mildly alkaline (pH 7.7). Contains very few fine carbonate filaments and many small charcoal flecks.

Auger: 75-105 cm, Btk2 continues, clay loam
105-200+ cm, Ck, clay loam

Nutria, Abandoned 2

Classification: Fine, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2073 m (6800 ft), 3.5% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned field
Landuser: ?
Described by Jeff Homburg and Lindsay Quam
Date: July 14, 1997

Ap 0-13 cm. Light brownish gray to olive brown (2.5Y 6/3) loam, grayish brown to light olive brown (2.5Y 5/3) moist; moderate thin plates (0 to 0.5 cm) and moderate fine granules; slightly hard, friable to firm, slightly sticky, slightly plastic; common very fine and few fine roots; many very fine vesicular and interstitial pores; <1% gravel; slightly effervescent; neutral (pH 7.1); abrupt wavy boundary.

BA 13-23 cm. Grayish brown to light yellowish brown (2.5Y 5.5/3) clay loam, dark grayish brown to light olive brown (2.5Y 4.5/3) moist; weak coarse and very coarse subangular blocks; hard, very firm, sticky, plastic; few thin clay films on ped faces and pores; common very fine roots; common very fine tubular pores; audibly effervescent; neutral (pH 7.2); clear smooth boundary.

Bt 23-42 cm. Grayish brown to light yellowish brown (2.5Y 5.5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; moderate very coarse prisms parting to moderate coarse and very coarse subangular blocks; hard, very firm, sticky, plastic; common moderately thick clay films on ped faces and pores; common very fine roots; common very fine tubular pores; slightly effervescent; neutral (pH 7.2); gradual smooth boundary.

Btk 42-75+ cm. Grayish brown to light yellowish brown (2.5Y 5.5/3) clay loam, dark grayish brown to light olive brown (2.5Y 4.5/3) moist; weak to moderate very coarse subangular blocks; hard, very firm, sticky, plastic; common moderately thick clay films on ped faces and pores; few very few roots; few very fine tubular pores; slightly to strongly effervescent; mildly alkaline (pH 7.8). Contains few fine carbonate filaments.

Auger: 75-190 cm, Btk continues, clay loam
190-220+ cm, Ck, sandy loam

Nutria, Abandoned 3

Classification: Fine-loamy, mixed, mesic Fluventic Haplustept
Geomorphic setting: Alluvial fan, elevation 2070 m (6790 ft), 2.5% slope
Parent material: Colluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Abandoned field
Landuser: Bennie Laate
Described by Jeff Homburg and Troy Lucio
Date: July 23, 1997

Ap 0-10 cm. Brown to yellowish brown (10YR 5/3.5) sandy loam, brown (10YR 5/3) moist; weak fine granules; soft, very friable, nonsticky, nonplastic; common very fine and fine and few medium roots; many very fine interstitial pores; 5% gravel; slightly effervescent; mildly alkaline (pH 7.8); clear wavy boundary.

Bw 10-24 cm. Brown to pale brown (10YR 5.5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; medium subangular blocks; slightly hard, friable, nonsticky, nonplastic; common fine and few fine and medium roots; common very fine interstitial pores; 8% gravel slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

C1 24-35 cm. Yellowish brown (10YR 5/4) sandy loam, dark yellowish brown (10YR 4/4) moist; massive; hard, firm, slightly sticky, slightly plastic; common very fine roots; common very fine interstitial pores; 10% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

C2 35-42 cm. Brown to yellowish brown (10YR 5/3.5) sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; massive; hard, firm, slightly sticky, slightly plastic; common very fine roots; common very fine interstitial pores; 5% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

C3 42-58 cm. Yellowish brown (10YR 5/4) sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; massive; hard, firm, slightly sticky, slightly plastic; common very fine roots; common very fine interstitial pores; 10% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

C4 58-68 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; massive; hard, firm, slightly sticky, slightly plastic; common very fine roots; common very fine interstitial pores; 5% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

2C5 68-90 cm. Brown to yellowish brown (10YR 5/3) sandy loam, brown to dark yellowish brown (10YR 4/3.5) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; common very fine roots; common very fine interstitial pores; 8% gravel; slightly effervescent; moderately alkaline (pH 8.0).

Auger: 90-120 cm, 2C5 continues, sandy loam
120-180 cm, 3Bt, clay loam

180-190 cm, 3C horizon, sandy loam
190+ cm, too sandy to auger

Nutria, Uncultivated 1

Classification: Fine, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2085 m (6840 ft), 6% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within uncultivated field used for grazing
Landuser: Bennie Laate
Described by Jeff Homburg and Vanissa Laahty
Date: June 10-11, 1997

A 0-6 cm. Light brownish gray (2.5Y 6/2) loam, dark grayish brown (2.5Y 4/2) moist; moderate thin plates (0-1 cm) and moderate fine granules; soft, very friable, slightly sticky, slightly plastic; common very fine and fine roots; common very fine vesicular and common very fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); clear smooth boundary.

BAt 6-17 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate coarse subangular blocks; slightly hard, friable to firm, sticky, plastic; few thin clay films on ped faces and pores; common very fine and fine roots; common very fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); gradual smooth boundary.

Bt 17-58 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate coarse and very coarse subangular blocks; hard, firm, sticky, plastic; common thin clay films on ped faces and pores; few very fine and fine roots; common very fine tubular pores; <2% gravel; slightly to strongly effervescent; moderately alkaline (pH 8.0); diffuse smooth boundary.

Btk 58-127 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate coarse and very coarse subangular blocks; hard, very firm, sticky, plastic; few thin clay films on ped faces and pores; few very fine roots; few very fine tubular pores; <2% gravel; slightly to strongly effervescent; moderately alkaline; (pH 8.2); gradual smooth boundary.

2BCk 127-150+ cm. Light brownish gray to light yellowish brown (2.5Y 6/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak coarse subangular blocks; hard, very firm, sticky, plastic; very few thin clay films on ped faces; few very fine roots; few very fine tubular pores; 5-10% gravel; slightly to strongly effervescent; moderately alkaline (pH 8.2).

Auger: 150-210 cm, 2BCkt horizon, clay loam, sandier with depth
210-240 cm, 3Btkb horizon, clay loam
240-285 cm, 3Btb horizon, clay loam
285-295+ cm, 3C, sandy loam

Nutria, Uncultivated 2

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2097 m (6880 ft), 3.5% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within uncultivated field used for grazing
Landuser: Cattle User's Association

Described by Jeff Homburg and Lindsay Quam
Date: June 25, 1997

A 0-6 cm. Grayish brown to light olive brown (2.5Y 5/3) fine sandy loam, dark grayish brown to olive brown (2.5Y 4/2.5) moist; weak fine granules; soft, very friable, nonsticky, nonplastic; many very fine and few fine roots; many very fine vesicular and few fine tubular pores; 2% gravel; neutral (pH 7.2); abrupt smooth boundary.

Bt1 6-25 cm. Grayish brown to olive yellow (2.5Y 5.5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/2.5) moist; weak medium subangular blocks; slightly hard to hard, firm, sticky, plastic; many thin to moderately thick clay films on ped faces and pores; common very fine and few fine roots; common very fine and fine tubular pores; 3-5% gravel; mildly alkaline (pH 7.4); gradual smooth boundary.

Bt2 25-44 cm. Grayish brown to light yellowish brown (2.5Y 5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak coarse prisms parting to weak to moderate medium subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; common very fine roots; common very fine and fine tubular pores; 3-5% gravel; mildly alkaline (pH 7.7); clear smooth boundary.

Btk1 44-65 cm. Grayish brown to light yellowish brown (2.5Y 5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; weak to moderate coarse and very coarse subangular blocks; very hard, very firm, sticky, plastic; many moderately thick clay films on ped faces and pores; few very fine roots; common very fine and fine tubular pores; 8% gravel; slightly effervescent; moderately alkaline; (pH 7.9); clear smooth boundary.

Btk2 65-83+ cm. Light brownish gray to light yellowish brown (2.5Y 6/3) clay loam, dark grayish brown to light olive brown (2.5Y 4.5/3) moist; weak medium subangular blocks; very hard, very firm, sticky, plastic; many thin to moderately thick clay films on ped faces; few very fine roots; few very fine tubular pores; 3% gravel; slightly to strongly effervescent; moderately alkaline (pH 8.0).

Auger: 83-90 cm, Btk horizon continues, clay loam
90-110 cm, C horizon, sandy loam
110-130 cm, 2Btb horizon, clay loam
130-220+ cm, 2C, sandy loam

Nutria, Uncultivated 3

Classification: Coarse-loamy, mixed, calcareous, mesic Aridic Ustifluvent
Geomorphic setting: Alluvial fan, elevation 2073 m (6800 ft), 3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Within uncultivated field used for grazing
Landuser: Fred Bowanne
Described by Jeff Homburg and Shawn Calevasia
Date: July 21, 1997

A 0-6 cm. Light olive brown to light yellowish brown (2.5Y 5.5/4) sandy loam, olive brown (2.5Y 4/4) moist; weak to moderate thin plates (0-0.5 cm) and weak to moderate fine granules; soft, very friable, slightly sticky, slightly plastic; common very fine and few fine roots; many very fine interstitial pores; 3% gravel; slightly effervescent; mildly alkaline (pH 7.9); abrupt smooth boundary.

BC 6-26 cm. Light olive brown (2.5Y 5/4) sandy loam, olive brown (2.5Y 4/4) moist; weak medium subangular blocks; soft, very friable, nonsticky, nonplastic; many thin to moderately thick clay films on ped faces and pores; common very fine and few fine roots; common very fine and fine tubular pores; 3-5% gravel; slightly effervescent; mildly alkaline (pH 7.4); abrupt smooth boundary.

2C1 26-35 cm. Grayish brown to light olive brown (2.5Y 5/3) loamy fine sand, dark grayish brown to olive brown (2.5Y 4/3) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; common very fine and few fine and medium roots; many very fine interstitial pores; 3-5% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

3C2 35-43 cm. Light olive brown (2.5Y 5/3.5) sandy loam, dark grayish brown to olive brown (2.5Y 4/3) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; common very fine roots; common very fine interstitial pores; 3% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

3C3 43-50 cm. Grayish brown to light olive brown (2.5Y 5/3) sandy loam, dark grayish brown to olive brown (2.5Y 4/3) moist; massive; slightly hard, firm, nonsticky, nonplastic; common very fine roots; common very fine interstitial pores; 3% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

4C4 50-55 cm. Grayish brown to light olive brown (2.5Y 5/3) sandy loam, dark grayish brown to olive brown (2.5Y 4/3) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; common very fine roots; common very fine interstitial pores; 10% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

5C5 55-63 cm. Grayish brown to light olive brown (2.5Y 5/3) loamy fine sand, dark grayish brown to olive brown (2.5Y 4/3) moist; massive; soft, very friable, nonsticky, nonplastic; common very fine roots; many very fine interstitial pores; 5% gravel; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

5C6 63-93 cm. Light olive brown (2.5Y 5/4) sandy loam, olive brown (2.5Y 4/4) moist; massive; soft to slightly hard, friable, nonsticky, nonplastic; common very fine roots; common very fine interstitial pores; 5% gravel; slightly effervescent; moderately alkaline (pH 8.0).

Auger: 83-90 cm, Btk horizon continues, clay loam
90-110 cm, C horizon, sandy loam
110-130 cm, 2Btb horizon, clay loam
130-220+ cm, 2C, sandy loam

Zuni Soil Study: Pedon Descriptions for Intensive Fields

Sanchez Field (Field 133) -Cultivated Soil

Classification: Fine-loamy, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2080m (6325 ft), 3% slope.
Parent material: Alluvium derived primarily from Cretaceous sandstone, mudstone, and shale.
Agricultural setting: Runoff field-historic and probably prehistoric use. Primary crop is maize.
Radiocarbon age: 24,320±1130 yr B.P. (Beta-63163) for charcoal and soil organic matter 160-220 cm depth.
Described by Jon Sandor, June 20, 1991.

Ap 0-23cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; cloddy (just plowed) plus moderate fine and medium subangular blocks and granules; slightly hard (clods hard), friable, sticky, plastic; few to common very fine, fine, and medium roots; common tubular pores; <1% gravel; neutral (pH 7.1); abrupt smooth to irregular boundary.

Bw 23-30cm. Brown (10YR 5/3) clay loam (few pockets of fine sandy loam), brown (10YR 4/3) moist; moderate medium subangular blocks; hard, friable to firm, sticky, plastic; few very fine, fine, medium, and coarse roots; common tubular and planar pores; <1% gravel; some audible carbonate; moderately alkaline (pH 7.9); clear smooth boundary.

Bk1 30-46cm. Light yellowish brown (10YR 5.5/4) clay loam (few pockets/strata of fine sandy loam and loamy sand), dark yellowish brown (10YR 4/4) moist; weak to moderate medium subangular blocks plus some strata; hard, friable, sticky, plastic; few very fine, fine, and medium roots; common tubular and planar pores; <1 to 5% gravel; common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.1); abrupt smooth boundary.

2Bk2 46-61cm. Light yellowish brown (10YR 5.5/4) fine sandy loam (few coarser strata), dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks plus some strata; slightly hard, friable, slightly sticky, slightly plastic; few roots; few tubular pores; 15 to 25% gravel in discontinuous lenses; common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.1); abrupt to clear smooth boundary.

2Bk3 61-88cm. Yellowish brown (10YR 5/4) sandy clay loam (few coarser strata), dark brown (10YR 3.5/3) moist; weak medium subangular blocks plus some strata; slightly hard, friable, slightly sticky, slightly plastic; few roots; few tubular pores; <1 to 5% gravel plus 15 to 25% gravel in discontinuous lenses; common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.1); abrupt to clear smooth boundary.

3?Btkb1 88-97cm. Yellowish brown (10YR 5/4) sandy clay loam, dark brown (10YR 3.5/3) moist; weak fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few roots; few planar pores; few thin clay coatings; <1 to 5% gravel; common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

3?Btkb2 97-113cm. Yellowish brown (10YR 5/4) sandy clay loam, dark yellowish brown (10YR 4/3.5) moist; weak and moderate fine and medium subangular blocks; slightly hard to hard, friable, slightly sticky, slightly plastic; few roots; common planar pores; common thin to moderately thick clay coatings; <1 to 3% gravel; common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.0); abrupt to clear smooth boundary.

4ABtkb 113-155+cm. Sandy clay loam, dark brown (10YR 3/3) moist; weak and moderate fine and medium subangular blocks and granules; slightly hard, friable, sticky, plastic; few roots; few tubular pores; common thin clay coatings; <1% gravel; few carbonate filaments; slightly effervescent; moderately alkaline (pH 8.2).

Note: augered below 155cm depth: gradual boundary to BC or C horizon by 170cm. Fine sandy loam to sandy loam to 310cm depth.

Sanchez Field (Field 133) -Uncultivated Soil

Classification: Fine, mixed, mesic Aridic Haplustalf
Geomorphic setting: Alluvial fan, elevation 2080m (6820 ft), 3% slope.
Parent material: Alluvium derived primarily from Cretaceous sandstone, mudstone, and shale.
Vegetation/cover: Big sagebrush (*Artemisia tridentata*), bare ground, grasses and forbs.
Agricultural setting: Just upslope from runoff field (probably former part of field or runoff management zone-see 1935 aerial photo).

Radiocarbon age: 8,010±80 yr B.P. (Beta-63164) for soil organic matter in 5Ab horizon, 134-155 cm depth. Described by Jon Sandor and Roman Pawluk, August 1, 1991.

A 0-7cm. Light yellowish brown (10YR 6/3.5) fine sandy loam, brown (10YR 5/3) moist; weak fine subangular blocks and weak fine and medium granules plus some strata; soft, very friable, nonsticky, nonplastic; common very fine, fine, medium, and coarse roots; few to common tubular pores; 5% fine gravel; slightly acid (pH 6.4); abrupt smooth boundary.

BA 7-18cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; moderate fine and medium subangular blocks and granules; hard, friable to firm, slightly sticky, slightly plastic; common very fine, fine, medium, and coarse roots; few to common tubular pores; few to many thin clay coatings; <2% gravel; neutral (pH 6.9); abrupt smooth boundary.

Bt 18-47cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; moderate medium prisms and fine angular blocks; very hard, firm, sticky, plastic; few to common very fine and fine and few medium, and coarse roots; common planar and few to common very fine tubular pores; many thin to moderately thick clay coatings; <2% gravel; neutral (pH 7.1); abrupt smooth boundary.

Btk1 47-65cm. Yellowish brown (10YR 5/3.5) clay loam, dark yellowish brown (10YR 4/3.5) moist; moderate fine and medium subangular blocks; hard, firm, sticky, plastic; few very fine, fine, medium, and coarse roots; common planar and few to common very fine tubular pores; common thin clay coatings; <2% gravel; few carbonate filaments; slightly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

2Btk2 65-77cm. Yellowish brown (10YR 5/4) very gravelly sandy clay loam, dark yellowish brown (10YR 4/4) moist; weak to moderate fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; few tubular pores; few to common thin clay coatings; 40 to 50% gravel; common carbonate filaments and seams; slightly effervescent; moderately alkaline (pH 7.9); clear smooth boundary. Some areas of gravelly clay loam.

2BC 77-116cm. Yellowish brown (10YR 5/4) gravelly sandy clay loam, dark yellowish brown (10YR 4/4) moist; mostly massive (stratified), some weak to moderate fine subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine, fine, and medium roots; few thin patchy clay coatings; 25-35% gravel; very few carbonate filaments; non-effervescent matrix mildly alkaline (pH 7.7); abrupt smooth boundary.

3C1 116-135cm. sandy clay loam, dark yellowish brown (10YR 4/4) moist; massive (partly stratified); slightly hard, very friable, slightly sticky, slightly plastic; few very fine, fine, and medium roots; ≤5% gravel; non-effervescent; mildly alkaline (pH 7.6); abrupt smooth boundary.

4C2 135-155+cm. gravelly sandy clay loam, yellowish brown (10YR 4.5/4) moist; massive (stratified); friable, slightly sticky, slightly plastic; few very fine, fine, and medium roots; 15% gravel; non-effervescent; mildly alkaline (pH 7.8).

5Ab 134-155cm. Clay loam, very dark grayish brown (10YR 3/2) moist; weak to moderate fine subangular blocks; slightly hard, friable, sticky, plastic; few very fine, fine, and medium roots; few tubular and planar pores; possible thin clay coatings; no gravel; slightly effervescent; mildly alkaline (pH 7.8). Note: This horizon occurs as pocket in south side of excavation.

Note: augered from 155 to 300cm depth: Below 4C2 gravelly sandy loam and sandy loam C horizons. Below 5Ab, loam ACb to 205cm then C horizon as elsewhere.

Field 75-Lower Uncultivated Soil

Classification: Sandy over loamy, mixed (calcareous), mesic Typic Ustifluvent
Geomorphic setting: Valley floor-toeslope, elevation 1928m (6325 ft), 2% slope.
Parent material: Alluvium derived from sedimentary rocks and other unconsolidated sediments, including aeolian sand.
Vegetation and cover: Rabbitbrush (*Chrysothamnus nauseousus*), grasses and forbs, bare ground.
Agricultural setting: Inactive runoff field-historic and probably prehistoric.
Described by Jon Sandor, June 18, 1991.

A1 0-7cm. Reddish brown (5YR 5/4) fine sandy loam, reddish brown (5YR 3.5/4) moist; weak fine and medium subangular blocks and granules; slightly hard, very friable, slightly sticky, slightly plastic; common to many very fine, fine, and few medium roots; common very fine and fine tubular pores with roots; no gravel; strongly effervescent; mildly alkaline (pH 7.8); clear smooth boundary. Upper 2cm soft to loose consistence.

A2 7-24cm. Light reddish brown (5YR 6/4) sandy clay loam, reddish brown (5YR 4/4) moist; weak medium subangular blocks and weak fine and medium plates; slightly hard, friable, slightly sticky, slightly plastic; few to common very fine and few fine and medium roots; common very fine and fine tubular pores; no gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

2AC 24-31cm. Light reddish brown (5YR 6/4) loamy fine sand, reddish brown (5YR 5/4) moist; weak fine and medium subangular blocks; soft, very friable, nonsticky, nonplastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.1); abrupt smooth boundary.

2C1 31-47cm. Light brown (7.5YR 6/4.5) loamy fine sand (fine strata 1-5mm thick, 31-40cm), strong brown (7.5YR 4.5/4.5) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine, fine, and medium roots; no gravel; strongly effervescent; moderately alkaline (pH 8.2); abrupt, smooth, slightly angled boundary.

2C2 47-56cm. Pink (7.5YR 7/4) loamy fine sand (some fine strata), brown (7.5YR 5/4) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary.

2C3 56-74cm. Pink (7.5YR 7/4) fine sand, brown (7.5YR 5/4) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.1); abrupt smooth boundary.

3C4 74-93cm. Light brown (7.5YR 6/4) very fine sandy loam, brown (7.5YR 5/4) moist and 5YR 4/4 for some finer sediment; massive; soft, very friable, slightly sticky, slightly plastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.2); abrupt smooth boundary.

3C5 93-113cm. Light brown (10YR 6/4) very fine sandy loam, yellowish brown to brown(10YR 5/4 to 7.5YR 4/4) moist; massive; soft, very friable, slightly sticky, slightly plastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.3); abrupt smooth boundary.

3C6 113-131cm. Light brown (10YR 6/4) loam, yellowish brown to brown(10YR 5/4 to 7.5YR 4/4) moist; massive; soft, very friable, slightly sticky, slightly plastic; few very fine and fine roots and one coarse root; no gravel; strongly effervescent; moderately alkaline (pH 8.3); abrupt smooth boundary.

3C7 131-145cm. Light brown (7.5YR 6/4) loam, yellowish brown to brown (7.5YR 5/4) moist; massive; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.3); abrupt smooth boundary.

3C8 145-160cm. Light reddish brown (5YR 6/4) loam, reddish brown (5YR 4/4) moist; massive; hard, firm, slightly sticky, slightly plastic; few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.4).

Note: Augered from 160cm depth: Strata of silty clay loam, fine sandy loam, and clay loam to 310cm depth.

Field 75-Lower Cultivated Soil

Classification: Sandy over loamy, mixed (calcareous), mesic Typic Ustifluvent

Geomorphic setting: Valley floor-toeslope, elevation 1928m (6325 ft), 2% slope.

Parent material: Alluvium derived from sedimentary rocks and other unconsolidated sediments, including eolian sediments.

Agricultural setting: Runoff field-historic and probably prehistoric. Profile described in currently fallow part of field. Primary crop is maize.

Radiocarbon age: 850$\pm$80 yr B.P. (Beta-63586) for organic matter-rich sediment and charcoal at top of 5C5 horizon, 95 cm depth.

Note: numerous animal burrows in field and some krotovina in upper part of profile.

Described by Jon Sandor and Jeff Homburg, June 15, 1991.

Ap1 0-4cm. Reddish brown (5YR 5/4) fine sandy loam, reddish brown (5YR 4/4) moist; weak fine and medium subangular blocks, single grain in parts of upper 1cm; soft, very friable, slightly sticky, slightly plastic; few to common very fine and fine roots; common very fine and fine tubular pores; no gravel; strongly effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary.

Ap2 4-29cm. Light reddish brown (5YR 5.5/4) fine sandy loam, reddish brown (5YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; few very fine tubular pores; no gravel; few fine carbonate filaments; strongly effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary.

2C1 29-49cm. Reddish yellow (7.5YR 7/5) fine sand, strong brown (7.5YR 5/6) moist; massive; soft, very friable, nonsticky, nonplastic; very few very fine and fine roots; no gravel; strongly effervescent; strongly alkaline (pH 8.5); abrupt smooth boundary.

3C2 49-70cm. Light brown (7.5YR 6/4) very fine sandy loam, brown (7.5YR 5/4) moist; massive; soft, very friable, slightly sticky, slightly plastic; very few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.4); abrupt U-shaped (across excavation) boundary.

3C3 70-79cm. Very fine sandy loam, brown (7.5YR 5/3) moist; massive; soft, very friable, slightly sticky, slightly plastic; very few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary. Layer includes 3cm thick discontinuous sand lens.

4C4 79-95cm. Loam, brown (7.5YR 5/4) moist; massive; soft, very friable, slightly sticky, slightly plastic; very few very fine and fine roots; no gravel; strongly effervescent; moderately alkaline (pH 8.3); abrupt smooth boundary. Note loamy very fine sand lens (10YR 6/4 moist) from 90-97cm in one area.

5C5 95-106cm. Very fine sandy loam (fine strata of very fine sandy loam and silt loam/silty clay loam), yellowish red (5YR 5/6-vfsl) to reddish brown (5YR 4/4-sil) moist (some greenish to yellowish colors also observed); massive; soft, very friable, slightly sticky, slightly plastic; very few very fine and fine roots; no gravel; violently effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary. Some 10YR colors?

6C6 106-124+cm. Clay loam (fine strata of very fine sandy loam and silt loam/silty clay loam), yellowish red (7.5YR 5/4-vfsl) to reddish brown (5YR 4.5/4-sil/sicl) moist; massive; hard, firm, slightly sticky to sticky, slightly plastic to plastic; very few very fine and fine roots; no gravel; violently effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary.

7C7 124-140+cm. Clay, reddish brown (5YR 4/4) moist; massive; very hard, very firm, sticky, very plastic; no roots observed; no gravel; violently effervescent; strongly alkaline (pH 8.5).

Note: Augered below 140cm depth: Strata of fine sandy to clayey sediments to 310cm depth.

Field 75-Upper Uncultivated Soil

Classification: Sandy, mixed, mesic Aridic Haplustalf
Geomorphic setting: backslope, elevation 1930m (6335 ft), 10% slope.
Parent material: Colluvium, alluvium, and eolian sediment derived primarily from Mesozoic sedimentary rocks.
Vegetation and cover: grasses and forbs, few shrubs like rabbitbrush (*Chrysothamnus nauseosus*).
Agricultural setting: 13 m outside of runoff agricultural field (matched to profile inside field).
Described by Jon Sandor and Wendy Fontenelle, June 13-14, 1991.

A 0-9cm. Brown (7.5YR 5/4) loamy sand, dark brown (7.5YR 4/3.5) moist; weak to moderate fine to medium subangular blocks and granules; soft, very friable, nonsticky, nonplastic; common to many very fine and common fine roots; few very fine and fine tubular pores; <1% gravel; neutral (pH 7.0); abrupt wavy boundary.

Bt 9-26cm. Brown (7.5YR 5/4) loamy sand, brown (7.5YR 4/4) moist; weak fine and medium subangular blocks to massive; slightly hard, friable, slightly sticky, nonplastic; few to common very fine and few fine roots; few very fine and fine tubular pores; few clay coatings bridging and staining sand grains; <1% gravel; moderately alkaline (pH 8.0); abrupt wavy boundary.

Btk 26-46cm. Brown (7.5YR 5/4) loamy sand, brown (7.5YR 4/4) moist; weak fine to coarse subangular blocks; slightly hard, very friable, nonsticky, nonplastic; few to common very fine and few fine, medium, and coarse roots; few very fine and fine tubular pores; few clay coatings bridging and staining sand grains; <1% gravel; few carbonate filaments along root channels; slightly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

Bk1 46-71cm. Strong brown (7.5YR 5/6) loamy sand, strong brown (7.5YR 4/6) moist; weak medium and coarse subangular blocks to massive; soft, very friable, nonsticky, nonplastic; few to common very fine and few fine, medium, and coarse roots; <1% gravel; common carbonate filaments and seams; strongly effervescent; moderately alkaline (pH 8.2); gradual wavy boundary.

Bk2 71-92cm. Strong brown (7.5YR 5/6) loamy sand, strong brown (7.5YR 4/6) moist; weak medium and coarse subangular blocks to massive; soft, very friable, nonsticky, nonplastic; few very fine, fine, medium, and coarse roots; <1% gravel; common carbonate filaments and seams; strongly effervescent; moderately alkaline (pH 8.3); gradual wavy boundary.

Bk3 92-110cm. Brown (7.5YR 5/4) loamy sand, brown (7.5YR 4/4) moist; massive with few weak medium and coarse subangular blocks; soft, very friable, nonsticky, nonplastic; few very fine, fine, medium, and coarse roots; <1% gravel; few to common carbonate filaments; slightly effervescent; moderately alkaline (pH 8.3); clear smooth boundary.

Bk4 110-126cm. Strong brown (7.5YR 5/5) loamy sand, strong brown (7.5YR 4/5) moist; massive with few weak medium and coarse subangular blocks; slightly hard, friable, nonsticky, nonplastic; few very fine, fine, medium, and coarse roots; <1% gravel; common carbonate filaments and seams; strongly effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

BC 126-160+cm. Strong brown (7.5YR 5.5/5) fine sand, strong brown (7.5YR 4.5/5) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine, fine, medium, and coarse roots; <1% gravel; few to common carbonate filaments and seams; strongly effervescent; moderately alkaline (pH 8.1).

Note: Clay coatings observed in thin section from surface down into Bt horizon. It is inferred that original surface horizon(s) were truncated, exposing part of original Bt horizon. An argillic horizon is then inferred even though the required clay increase is marginal. The other possible classification is Mixed, mesic Aridic Ustipsamment. Augered below 160cm depth calcareous loamy sand and sand C horizons to 325cm depth.

Field 75-Upper Cultivated Soil

Classification: Sandy, mixed, mesic Aridic Haplustalf
Geomorphic setting: backslope, elevation 1930m (6335 ft), 10% slope.
Parent material: Colluvium, alluvium, and eolian sediment derived primarily from Mesozoic sedimentary rocks.
Agricultural setting: Runoff field-historic and probably prehistoric. Primary crop is maize.
Described by Jon Sandor and Wendy Fontenelle, June 12-13, 1991.

Ap1 0-10cm. Brown (7.5YR 5/4) loamy sand, brown (7.5YR 4/4) moist; weak fine and medium subangular blocks and granules; soft, very friable, nonsticky, nonplastic; common very fine and few fine roots; common various pores; <1% gravel; mildly alkaline (pH 7.6); abrupt smooth boundary.

Ap2 10-32cm (varies from 21 to 32cm). Strong brown (7.5YR 5/5) loamy sand, brown (7.5YR 4/4) moist; weak fine and medium subangular blocks and granules, partly massive and compacted (plow pan); slightly hard, friable, nonsticky, nonplastic; few very fine roots; <1% gravel; moderately alkaline (pH 8.1); abrupt smooth boundary. Note: curved streaks of sand 12-28cm (7.5YR 6/3 dry, 7.5YR 4/3 moist), probably from plowing..

Ab 32-36cm. Brown (7.5YR 5/3.5) loamy sand, brown (7.5YR 4/3) moist; weak fine and medium subangular blocks and granules; slightly hard, friable, nonsticky, nonplastic; few very fine roots; few very fine and fine tubular pores; <1% gravel; moderately alkaline (pH 8.3); abrupt smooth boundary.

Bt1 36-47cm. Brown (7.5YR 4/4) loamy fine sand, dark brown (7.5YR 3.5/4) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few to common very fine and fine roots; few very fine and fine tubular pores; few clay coatings bridging and staining sand grains; <1% gravel; moderately alkaline (pH 8.3); clear smooth boundary.

Bt2 47-54cm. Brown (7.5YR 4/4) loamy sand, dark brown (7.5YR 3.5/4) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few clay coatings bridging and staining sand grains; few to common very fine and fine roots; few very fine and fine tubular pores; few clay coatings bridging and staining sand grains; <1% gravel; few fine carbonate filaments along root channels (noneffervescent in matrix); moderately alkaline (pH 8.3); clear smooth boundary.

Bk1 54-69cm. Brown (7.5YR 4/4) loamy sand, dark brown (7.5YR 3.5/4) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; few very fine and fine tubular pores; <1% gravel; few to common carbonate filaments and soft masses; slightly effervescent; moderately alkaline (pH 8.3); clear smooth boundary.

Bk2 69-80cm. Strong brown (7.5YR 4/6) loamy sand, strong brown (7.5YR 4/6) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; few very fine and fine tubular pores; <1% gravel; few to common carbonate filaments and soft masses; slightly effervescent; moderately alkaline (pH 8.3); clear smooth boundary.

Bk3 80-94+cm. Strong brown (7.5YR 4/6) loamy sand, strong brown (7.5YR 4/6) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; few very fine and fine tubular pores; <1% gravel; few to common carbonate filaments and soft masses; slightly effervescent; moderately alkaline (pH 8.3); gradual smooth to wavy boundary.

Bk4 94-129+cm. Reddish yellow (7.5YR 6/5) loamy fine sand, strong brown (7.5YR 5/5) moist; weak medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few very fine roots; few very fine and fine tubular pores and one krotovina; <1% gravel (5% gravel stratum near base); few carbonate filaments and soft masses; slightly effervescent; moderately alkaline (pH 8.4); abrupt smooth boundary.

BC or C 129-160+cm. Reddish yellow (7.5YR 6/5) fine sand, strong brown (7.5YR 5/5) moist; massive; soft, very friable, nonsticky, nonplastic; few very fine roots; <1% gravel; few carbonate filaments and soft masses; slightly effervescent; strongly alkaline (pH 8.6); abrupt smooth boundary. Note: concentration of 50-75% gravel from 129-136cm in part of exposure.

Note: Clay coatings observed in thin section from surface down into Bt horizon. It is inferred that original surface horizon(s) were truncated, exposing part of original Bt horizon. An argillic horizon is then inferred even though the required clay increase is not present. The other possible classification is Mixed, mesic Aridic Ustipsamment. Augered below 160cm depth-calcareous loamy sand and sand C horizons to 300cm depth.

Weekoty Field-Cultivated Soil

Classification: Fine-loamy, mixed, mesic, Aridic Argiustoll
Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Cultivated field (currently fallow)
Landuser: Fred Weekoty
Described by Jon Sandor
Date: July 29, 1996

Ap 0-17 cm. Brown (10YR 5/3) sandy loam, dark brown (10YR 3/3) moist; weak thin plates in upper 5 cm, weak fine granules and weak to moderate fine and medium subangular blocks; soft to slightly hard, very friable, slightly sticky, slightly plastic; few to common very fine and fine roots; 5% gravel; neutral (pH 6.8); abrupt to clear smooth boundary.

ABt 17-28 cm. Brown (10YR 5/3) sandy loam, dark brown (10YR 3/3) moist; weak to moderate fine and medium subangular blocks; slightly hard to hard, friable, slightly sticky, slightly plastic; few to common thin clay films on ped faces and pores; few very fine and fine roots; 5-10% gravel; neutral (pH 6.8); abrupt to clear smooth boundary.

Bt 28-68 cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; moderate fine and medium prisms parting to weak to moderate fine and medium subangular blocks; hard, firm, slightly sticky to sticky, slightly plastic to plastic; common thin clay films on ped faces and pores; few very fine and fine roots; tubular and planar pores; 5% gravel; neutral (pH 6.9); abrupt irregular boundary. Charcoal flecks scattered throughout.

Bt or BCt 68-81 cm. Yellowish brown (10YR 5/4) sandy loam to sandy clay loam, dark yellowish brown (10YR 4/4) moist; weak fine and medium subangular blocks; hard, friable, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; few very fine, fine, and medium roots; 5% gravel; mildly alkaline (pH 7.4); abrupt to clear smooth boundary.

Bt or BCt 81-105 cm. Yellowish brown (10YR 5/4) fine sandy loam, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and fine roots; 5% gravel; moderately alkaline (pH 8.0); effervescent; abrupt to clear smooth boundary. Contains a few carbonate filaments.

2Btk1 105-141 cm. Yellowish brown (10YR 5/4) clay loam, dark yellowish brown (10YR 3/4) moist; moderate medium subangular blocks; slightly hard, friable, sticky, plastic; few very fine and fine roots; 5% gravel; moderately alkaline (pH 8.0); effervescent abrupt smooth boundary. Contains a few carbonate filaments.

2 or 3 Btk2 141-150+ cm. Yellowish brown (10YR 5/4) sandy clay loam, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, slightly sticky to sticky, slightly plastic; few very fine roots; 5% gravel; moderately alkaline (pH 8.4); strongly effervescent. Contains many carbonate filaments and an 8-cm wide krotovina.

Auger: 150-210 cm, 2 or 3BCtk horizon, loamy sand, charcoal flecks scattered throughout, effervescent, few carbonate threads and few clay films
210-230 cm, 2 or 3BCtk horizon, loam, effervescent, few carbonate threads and few clay films
230-300 cm, 2 or 3BCtk horizon, loam, effervescent, few carbonate threads and few clay films, 5-10% gravel throughout

Weekoty Field-Uncultivated Soil

Classification: Fine-loamy, mixed, mesic, Aridic Argiustoll
Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field
Landuser: Fred Weekoty
Described by Jon Sandor
Date: July 30, 1996

A 0-9 cm. Brown (10YR 5/3) loam, dark grayish brown (10YR 4/2) moist; weak thin plates in upper 0.5 cm, weak to moderate fine and medium granules; soft, very friable to friable, slightly sticky, slightly plastic; common very fine and fine roots; many very fine vesicular pores; <5% gravel; neutral (pH 7.0); abrupt smooth boundary.

BAt 9-27 cm. Brown (10YR 5/3) sandy loam, dark grayish brown (10YR 4/2) moist; weak fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few coarse roots; common very fine and fine tubular and few very fine vesicular pores; <5% gravel; mildly alkaline (pH 7.5); clear smooth boundary.

Bt1 27-59 cm. Grayish brown to brown (10YR 5/2.5) sandy clay loam to loam, dark to very dark grayish brown (10YR 3.5/2) moist; moderate medium prisms parting to weak fine and medium subangular blocks; hard, friable to firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and fine roots; many very fine and few fine tubular pores; <5% gravel; slightly acidic (pH 6.5); clear smooth boundary.

Bt2 59-82 cm. Brown (10YR 5/3) loam, dark brown (10YR 3/3) moist; moderate fine and medium prisms parting to weak fine and medium subangular blocks; very hard, very firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few to common fine roots; many fine and few fine tubular pores; 10% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

BCt1 82-101 cm. Yellowish brown (10YR 5/4) loamy sand, brown to dark yellowish brown (10YR 4/3.5) moist; massive; soft, very friable, nonsticky, nonplastic; few fine roots; few very fine tubular pores; 5-10% gravel and one 15 cm cobble; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains very few 1 mm laminations.

BCt2 101-132 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; hard, friable firm, slightly sticky, slightly plastic; few very fine and fine roots; common very fine and few fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains common 1 mm laminations and charcoal flecks.

BCt3 132-150+ cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; slightly hard, very friable, slightly sticky, slightly plastic; few medium roots; common very fine interstitial pores; 5% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains many 1-3 mm laminations, and a charcoal lens in the lower part.

Auger: 150-170 cm, BCt3 horizon, fine sandy loam, 5% gravel, noncalcareous, has clay films
170-220 cm, BCtk1 horizon, sandy loam, 5% gravel, carbonate filaments and few clay films
220-230 cm, BCtk2 horizon, loam, carbonate filaments and few clay films
230-275 cm, BCtk3 horizon, fine sandy loam, 5% gravel, carbonate filaments and few clay films, effervescent
275-300 cm, 2BCtk4 horizon, clay loam, clay coatings
300-310 cm+, 2 BCt?k5 horizon, loam,

Field 153-Cultivated Field

Classification: Fine-loamy, mixed, mesic Aridic Ustifluvent
Geomorphic setting: Distal fan toeslope/alluvial plain, elevation 2070 m (6790 ft), 1% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Cultivated field used for grazing
Landuser: Bennie Laate
Described by Jon Sandor and Jay Norton
Date: August 5, 1996

Ap 0-23 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) loam, dark grayish brown to olive brown (2.5Y 4/3) moist; moderate fine and medium subangular blocks and granules; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary.

2C1 (sandy) 23-37 cm. Light yellowish brown (2.5Y 6/4) sandy clay, olive brown (2.5Y 4/4) moist; finely stratified; slightly hard, friable to firm, slightly sticky, slightly plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary.

2C1 (silty) 23-37 cm. Light yellowish brown (2.5Y 6/4) silty clay loam, light olive brown (2.5Y 5/4) moist; massive, finely stratified; hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary. Contains 1-mm wide pellets.

2C2 37-68 cm. Grayish brown to light olive brown (2.5Y 5/3) clay loam, dark grayish brown to olive brown (2.5Y 4/3) moist; massive, weakly stratified, few weak subangular blocks; hard, firm, sticky, plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); clear smooth boundary. Contains 1-mm wide pellets.

3C3 (sandy) 68-96 cm. Light olive brown to light yellowish brown (2.5Y 5.5/4) sandy loam, olive brown (2.5Y 4/3.5) moist; massive, finely stratified; soft, very friable, slightly sticky, slightly plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline; (pH 7.8-8.0); abrupt smooth boundary.

3C3 (silty) 68-96 cm. Light olive brown (2.5Y 5/3.5) silty clay loam, olive brown (2.5Y 4/3.5) moist; massive, finely stratified; slightly hard to hard, firm, slightly sticky, slightly plastic; very few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary.

4Btb 96-119 cm. Light brownish gray to grayish brown (2.5Y 5.5/3) silty clay, dark grayish brown to olive brown (2.5Y 4/3) moist; weak medium subangular blocks to massive (compressed); very hard, very firm, very sticky, very plastic; many thin to moderately thick clay films on ped faces and pores; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); clear smooth boundary.

4Btkb 119-140 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) silty clay, olive brown (2.5Y 4/3.5) moist; weak medium subangular blocks to massive (compressed); very hard, very firm, sticky to very sticky, very plastic; common thin to moderately thick clay films on ped faces and pores; very few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary.

4BCtkb 140-150+ cm. Light brownish gray to light yellowish brown (2.5Y 6/4) silt loam, light olive brown (2.5Y 5/4) moist; massive; slightly hard, firm, slightly sticky, plastic; very few thin clay films on ped faces and pores; very few very fine and fine roots; few very fine and fine tubular pores; effervescent; mildly to moderately alkaline (pH 7.8-8.0).

Auger: 150-200 cm, 4BCtkb horizon continues, silty clay loam, sandier with depth, effervescent
200-300 cm, silty clay, carbonate filaments, effervescent

Field 153-Uncultivated Field

Classification: Fine-loamy, mixed, mesic Aridic Ustifluvent
Geomorphic setting: Distal fan toeslope/alluvial plain, elevation 2070 m (6790 ft), 1% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Bennie Laate
Described by Jon Sandor
Date: August 5, 1996

A 0-17 cm. Light brownish gray to light olive brown (2.5Y 5.5/3) loam with some very fine sand, dark grayish brown to olive brown (2.5Y 4/3) moist; weak fine and medium subangular blocks, weak fine granules, and some fine plates or laminae; slightly hard, friable, slightly sticky, slightly plastic; few very fine and fine roots; effervescent; mildly to moderately alkaline (pH 7.8-8.0); abrupt smooth boundary.

2C1 (silty) 17-40 cm. Light yellowish brown (2.5Y 6/4) silt loam to silty clay loam, olive brown (2.5Y 4/4) moist; massive, finely stratified; slightly hard to hard, friable, slightly sticky, plastic; common to many very fine and fine roots; slightly effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Contains 2-3 cm thick laminations alternating with 11 cm thick stratum of loamy fine sand (described below)

2C1 (sandy) 17-40 cm. Light yellowish brown (2.5Y 6/4) loamy fine sand, olive brown (2.5Y 4/4) moist; finely stratified; soft, very friable, nonsticky, nonplastic; common to many very fine and fine roots; effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.

3C2 40-80 cm. Light yellowish brown (2.5Y 6/4) silt loam, light olive brown (2.5Y 5/4) moist; massive, finely stratified; slightly hard, friable, slightly sticky, plastic; few very fine and fine roots; effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary. Contains charcoal in lenses from 38 to 48 cm.

4C3 80-107 cm. Light yellowish brown (2.5Y 6/4) very fine sandy loam to loam, light yellowish brown to light olive brown (2.5Y 5.5/4) moist; massive, finely stratified; slightly hard to hard, friable, slightly sticky, slightly plastic; few to common very fine, fine, and medium roots; effervescent; mildly alkaline (pH 7.8); abrupt smooth boundary.
Interstratified with very fine and fine sand and 1-2 mm silty laminae.

5Btb 107-126 cm. Light brownish gray to light yellowish brown (2.5Y 6/3) silty clay, olive brown (2.5Y 4/3.5) moist; moderate fine and medium angular and subangular blocks; very hard, firm, sticky to very sticky, very plastic; common thin to moderately thick clay films on ped faces and pores; few very fine and fine roots; mildly alkaline (pH 7.8; clear smooth boundary.

5Btkb 126-150+ cm. Dark grayish brown to olive brown (2.5Y 6/3) silty clay, olive brown (2.5Y 4/3) moist; moderate fine and medium angular and subangular blocks; very hard, firm, sticky to very sticky, very plastic; few very fine and fine roots; audibly to very slightly effervescent; mildly alkaline (pH 7.8).

Auger: 140-155 cm, 5Btkb horizon continues, silty clay
155-165 cm, silt loam to silty clay loam, carbonate filaments, strongly effervesces
165-290 cm, silty clay loam with some fine sand, some areas with carbonate filaments, effervescent

Ant and Soil Study: Pedon Descriptions

Ant Mound and Submound

Classification: Fine-loamy, mixed, mesic Aridic Haplustalfs
Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Fred Weekoty
Described by Jeff Homburg
Date: July 14, 1998

mound 0-18 cm. Brown (10YR 5/3) gravelly fine sandy loam, brown (10YR 4/3) moist; moderate thin plates and weak to moderate fine granules; soft, very friable, slightly sticky, slightly plastic; few very fine roots; few medium and common very fine tubular and common fine and very fine vesicular pores; <25% gravel; slightly acid (pH 6.5); clear smooth boundary.

mound +18-10 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; moderate fine granules; soft, very friable, nonsticky, nonplastic; common very fine and fine roots; common very fine and fine tubular; <10% gravel; slightly acid (pH 6.5); abrupt smooth boundary.

mound +10-0 cm. Brown (10YR 5/3) gravelly sandy loam, brown (10YR 4/3) moist; weak to moderate fine granules; soft to slightly hard, very friable, nonsticky, nonplastic; few thin clay films on ped faces and pores; few thin clay films on ped faces and pores; many very fine and common fine roots; many very fine tubular pores; <18% gravel; mildly alkaline (pH 7.5); abrupt smooth boundary.

A 0-10 cm. Brown (10YR 5/3) fine sandy loam, dark brown (10YR 3/3) moist; weak to moderate fine granules and weak to moderate medium and coarse subangular blocks; slightly hard, friable to firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; many very fine and common fine roots; common very fine tubular pores; 5% gravel; moderately alkaline (pH 8.0); slightly effervescent, clear smooth boundary.

Bt1 10-20 cm. Brown (10YR 4.5/4) loam to sandy clay loam, dark brown (10YR 3.5/3) moist; moderate to strong medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; common very fine and fine roots; common very fine and few medium tubular pores; 9% gravel; moderately alkaline (pH 7.9); slightly effervescent; clear smooth boundary.

Bt2 10-35 cm. Brown (10YR 4/3) loam to sandy clay loam, brown (10YR 3.5/3) moist; moderate to strong medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; many thin clay films on ped faces and pores; common very fine and fine roots; common very fine and few medium tubular pores; 8% gravel; moderately alkaline (pH 7.9); slightly effervescent; abrupt smooth boundary.

Btk1 35-57 cm. Brown (10YR 4/3) loamy sand, dark brown (10YR 3/3) moist; weak medium and coarse subangular blocks; soft; very friable, nonsticky, nonplastic; few thin clay films on ped faces and pores; common very fine and fine roots; common very fine and fine and few medium tubular pores; 8% gravel; moderately alkaline (pH 8.0); slightly effervescent; clear smooth boundary.

Btk2 57-72 cm. Brown to pale brown (10YR 5.5/4) sandy loam, brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; soft, very friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few medium roots; common very fine and few fine and medium tubular pores; 8% gravel; moderately alkaline (pH 8.0); effervescent; gradual smooth boundary.

BCtk 72-106 cm. Brown (10YR 5/3) sandy loam, brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and fine roots; few very fine tubular pores; 8% gravel; moderately alkaline (pH 8.0); effervescent; gradual smooth boundary.

2BCtk 106-123+ cm. Brown (10YR 5/3) fine sandy loam; brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and fine roots; few very fine tubular pores; 20% gravel; moderately alkaline (pH 8.0); effervescent.

Note: 3-16 cm wide and 1-2 cm tall ant chambers connected by 5-9 mm tunnels found between 20 and 143 cm depth, most of which are concentrated at 0-40 cm depth.

Clearing Next to Ant Mound

Classification: Fine-loamy, mixed, mesic Aridic Haplustalfs

Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field used for grazing
Landuser: Fred Weekoty
Described by Jeff Homburg
Date: July 14, 1998

A1 0-3 cm. Pale brown (10YR 6/3) fine sandy loam, brown (10YR 5/3) moist; moderate thin plates from 0-0.5 cm and weak to moderate fine granules from 0.5-3 cm; soft, friable, slightly sticky, slightly plastic; few very fine roots; common very fine and fine tubular pores; 20% gravel; acid (pH 6.0); abrupt smooth boundary.

A2 3-11 cm. Pale brown (10YR 6/3) fine sandy loam, brown (10YR 5/3) moist; weak to moderate fine granules and weak to moderate medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; common very fine and fine roots; few very fine tubular pores; 15% gravel; slightly acidic (pH 6.5); clear smooth boundary.

ABt 11-18 cm. Brown (10YR 4.5/3) loam to sandy clay loam, dark brown (10YR 3/3) moist; moderate to strong medium and coarse subangular blocks; slightly hard, firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few medium roots; common very fine medium tubular pores; 5% gravel; acidic (pH 6.0); clear smooth boundary.

BAt 18-25 cm. Brown (10YR 4.5/3) loam to sandy clay loam, dark brown (10YR 3/3) moist; moderate to strong medium and coarse subangular blocks; hard; firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and fine roots; common very fine and fine tubular pores; 5% gravel; slightly acidic (pH 6.5); clear smooth boundary.

Bt1 25-59 cm. Brown (10YR 5/3) loam to sandy clay loam, brown (10YR 4/3) moist; moderate to strong medium and coarse subangular blocks; hard, firm, slightly sticky, slightly plastic; many thin clay films on ped faces and pores; common very fine and fine and few medium roots; common very fine and few fine and medium tubular pores; 8-9% gravel; neutral (pH 7.0); effervescent; abrupt smooth boundary. Contains charcoal flecks.

Bt2 59-68 cm. Yellowish brown (10YR 5/4) loamy sand, brown to dark yellowish brown (10YR 4/3.5) moist; weak to moderate medium subangular blocks; soft; friable, nonsticky, nonplastic; few thin clay films on ped faces and pores; common very fine and fine roots; common very fine and fine and few medium tubular pores; 7% gravel; moderately alkaline (pH 8.0); effervescent; gradual smooth boundary. Contains charcoal flecks.

Btk 68-96 cm. Brown (10YR 5/3) sandy loam; brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; soft, very friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few medium roots; common very fine and few fine and medium tubular pores; 8% gravel; moderately alkaline (pH 8.0); slightly effervescent; carbonate threads visible on ped faces; gradual smooth boundary.

BCtk 96-124+ cm. Brown (10YR 5/3) sandy loam; brown (10YR 4/3) moist; weak to moderate medium and coarse subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and fine roots; few very fine tubular pores; 12% gravel; moderately alkaline (pH 8.0); slightly effervescent.

Fallow Soil

Classification: Fine-loamy, mixed, mesic, Aridic Argiustolls
Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Cultivated field (currently fallow)
Landuser: Fred Weekoty
Described by Jon Sandor
Date: July 29, 1996

Ap 0-17 cm. Brown (10YR 5/3) sandy loam, dark brown (10YR 3/3) moist; weak thin plates in upper 5 cm, weak fine granules and weak to moderate fine and medium subangular blocks; soft to slightly hard, very friable, slightly sticky, slightly plastic; few to common very fine and fine roots; 5% gravel; neutral (pH 6.8); abrupt to clear smooth boundary.

ABt 17-28 cm. Brown (10YR 5/3) sandy loam, dark brown (10YR 3/3) moist; weak to moderate fine and medium subangular blocks: slightly hard to hard, friable, slightly sticky, slightly plastic; few to common thin clay films on ped faces and pores; few very fine and fine roots; 5-10% gravel; neutral (pH 6.8); abrupt to clear smooth boundary.

Bt 28-68 cm. Brown (10YR 5/3) clay loam, brown (10YR 4/3) moist; moderate fine and medium prisms parting to weak to moderate fine and medium subangular blocks; hard, firm, slightly sticky to sticky, slightly plastic to plastic; common thin clay films on ped faces and pores; few very fine and fine roots; tubular and planar pores; 5% gravel; neutral (pH 6.9); abrupt irregular boundary. Charcoal flecks scattered throughout.

Bt or BCt 68-81 cm. Yellowish brown (10YR 5/4) sandy loam to sandy clay loam, dark yellowish brown (10YR 4/4) moist; weak fine and medium subangular blocks; hard, friable, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; few very fine, fine, and medium roots; 5% gravel; mildly alkaline (pH 7.4); abrupt to clear smooth boundary.

Bt or BCt 81-105 cm. Yellowish brown (10YR 5/4) fine sandy loam, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few very fine and fine roots; 5% gravel; moderately alkaline (pH 8.0); effervescent; abrupt to clear smooth boundary. Contains a few carbonate filaments.

2Btk1 105-141 cm. Yellowish brown (10YR 5/4) clay loam, dark yellowish brown (10YR 3/4) moist; moderate medium subangular blocks; slightly hard, friable, sticky, plastic; few very fine and fine roots; 5% gravel; moderately alkaline (pH 8.0); effervescent; abrupt smooth boundary. Contains a few carbonate filaments.

2 or 3 Btk2 141-150+ cm. Yellowish brown (10YR 5/4) sandy clay loam, dark yellowish brown (10YR 4/4) moist; weak medium subangular blocks; slightly hard, friable, slightly sticky to sticky, slightly plastic; few very fine roots; 5% gravel; moderately alkaline (pH 8.4); strongly effervescent. Contains many carbonate filaments and an 8-cm wide krotovina.

Auger: 150-210 cm, 2 or 3BCtk horizon, loamy sand, charcoal flecks scattered throughout, effervescent, few carbonate threads and few clay films
210-230 cm, 2 or 3BCtk horizon, loam, effervescent, few carbonate threads and few clay films
230-300 cm, 2 or 3BCtk horizon, loam, effervescent, few carbonate threads and few clay films, 5-10% gravel throughout

Uncultivated Soil

Classification: Fine-loamy, mixed, mesic, Aridic Argiustolls
Geomorphic setting: Alluvial fan, elevation 2088 m (6850 ft), 2-3% slope
Parent material: Alluvium derived from Cretaceous sedimentary rocks weathered from the Gallup and Crevasse Canyon formations
Agricultural setting: Uncultivated field
Landuser: Fred Weekoty
Described by Jon Sandor
Date: July 30, 1996

A 0-9 cm. Brown (10YR 5/3) loam, dark grayish brown (10YR 4/2) moist; weak thin plates in upper 0.5 cm, weak to moderate fine and medium granules; soft, very friable to friable, slightly sticky, slightly plastic; common very fine and fine roots; many very fine vesicular pores; <5% gravel; neutral (pH 7.0); abrupt smooth boundary.

BAt 9-27 cm. Brown (10YR 5/3) sandy loam, dark grayish brown (10YR 4/2) moist; weak fine and medium subangular blocks; slightly hard, friable, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; common very fine and fine and few coarse roots; common very fine and fine tubular and few very fine vesicular pores; <5% gravel; mildly alkaline (pH 7.5); clear smooth boundary.

Bt1 27-59 cm. Grayish brown to brown (10YR 5/2.5) sandy clay loam to loam, dark to very dark grayish brown (10YR 3.5/2) moist; moderate medium prisms parting to weak fine and medium subangular blocks; hard, friable to firm, slightly sticky, slightly plastic; common thin clay films on ped faces and pores; common very fine and fine roots; many very fine and few fine tubular pores; <5% gravel; slightly acidic (pH 6.5); clear smooth boundary.

Bt2 59-82 cm. Brown (10YR 5/3) loam, dark brown (10YR 3/3) moist; moderate fine and medium prisms parting to weak fine and medium subangular blocks; very hard, very firm, slightly sticky, slightly plastic; few thin clay films on ped faces and pores; few to common fine roots; many fine and few fine tubular pores; 10% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary.

BCt1 82-101 cm. Yellowish brown (10YR 5/4) loamy sand, brown to dark yellowish brown (10YR 4/3.5) moist; massive; soft, very friable, nonsticky, nonplastic; few fine roots; few very fine tubular pores; 5-10% gravel and one 15 cm cobble; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains very few 1mm thick laminae.

BCt2 101-132 cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; hard, friable firm, slightly sticky, slightly plastic; few very fine and fine roots; common very fine and few fine tubular pores; <2% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains common 1mm thick laminae and charcoal flecks.

BCt3 132-150+ cm. Brown (10YR 5/3) loam, brown (10YR 4/3) moist; massive; slightly hard, very friable, slightly sticky, slightly plastic; few medium roots; common very fine interstitial pores; 5% gravel; moderately alkaline (pH 8.0); abrupt smooth boundary. Contains many 1-3 mm thick laminae, and a charcoal lens in the lower part.

Auger: 150-170 cm, BCt3 horizon, fine sandy loam, 5% gravel, noncalcareous, has clay films
170-220 cm, BCtk1 horizon, sandy loam, 5% gravel, carbonate filaments and few clay films
220-230 cm, BCtk2 horizon, loam, carbonate filaments and few clay films

230-275 cm, BCtk3 horizon, fine sandy loam, 5% gravel, carbonate filaments and few clay films, effervescent

275-300 cm, 2BCtk4 horizon, clay loam, clay coatings

300-310 cm+, 2 BCt?k5 horizon, loam

APPENDIX B. SOIL DATA FOR ZUNI STUDY

Chemical and Physical Soil Data for Intensive (Paired) Transects

Field and Sampling Point	pH	Org C (g/kg)	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	C:N Ratio	Inorg. C (g/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
Laate, Cultivated																				
C-1	7.7	9.5	0.71	–	–	13.4	–	12.3	420	1.55	0.1	0.2	4.6	24	14	43	15	17	32	26
C-2	7.7	12.3	0.85	–	–	14.5	–	11.5	466	1.53	0.0	0.3	3.1	18	14	36	18	21	39	25
C-3	7.6	10.9	0.76	–	–	14.4	–	10.7	465	1.54	0.0	0.2	2.4	17	17	37	19	20	39	24
C-4	7.8	10.4	0.76	–	–	13.6	–	11.5	455	1.46	0.0	0.2	3.5	21	14	37	20	18	37	25
C-5	7.7	11.4	0.76	–	–	15.0	–	11.7	427	1.54	0.1	0.3	2.6	17	16	34	21	19	40	25
C-6	7.7	9.8	0.76	–	–	12.6	–	11.7	456	1.59	0.0	0.2	2.6	21	19	41	20	15	36	23
C-7	7.7	8.1	0.67	–	–	12.1	–	10.5	401	1.54	0.0	0.2	3.9	29	17	49	17	12	29	22
C-8	7.8	9.3	0.69	–	–	13.4	–	10.2	396	1.55	0.1	0.2	3.6	26	16	46	18	13	31	23
C-9	7.8	10.2	0.74	–	–	13.8	–	8.5	405	1.46	0.1	0.3	4.2	22	17	42	19	17	35	23
C-10	7.8	8.0	0.65	–	–	12.3	–	10.1	381	1.56	0.1	0.6	8.1	30	12	51	16	13	29	20
Laate, Uncultivated																				
U-1	7.8	7.9	0.63	–	–	12.6	–	8.8	430	1.46	0.0	0.2	2.4	31	17	50	15	12	27	23
U-2	7.2	17.5	1.26	–	–	13.9	–	20.2	524	1.40	0.1	0.2	3.2	20	14	36	20	18	38	26
U-3	7.8	6.6	0.60	–	–	11.1	–	10.7	383	1.46	0.0	0.1	3.0	36	16	54	16	12	27	19
U-4	7.8	13.0	0.82	–	–	15.9	–	11.0	441	1.45	0.1	0.9	9.2	19	22	48	11	15	26	25
U-5	7.8	18.3	1.10	–	–	16.6	–	9.3	470	1.34	0.0	0.2	2.1	13	17	30	23	20	43	27
U-6	7.7	9.3	0.72	–	–	12.9	–	11.5	460	1.46	0.1	0.2	1.9	27	16	45	14	14	28	27
U-7	7.7	7.5	0.63	–	–	11.8	–	9.5	415	1.43	0.1	0.2	1.3	23	18	40	21	14	34	25
U-8	7.7	13.3	0.92	–	–	14.5	–	13.6	479	1.50	0.0	0.2	2.5	26	16	45	19	13	32	23
U-9	7.9	15.3	0.88	–	–	17.4	–	8.9	460	1.26	0.1	0.2	0.4	12	20	31	23	18	41	28
U-10	7.6	16.7	1.07	–	–	15.6	–	13.5	506	1.40	0.1	0.3	0.4	5	20	24	27	21	46	29
Weekaty, Cultivated																				
C-1	6.6	11.3	0.94	–	–	12.0	–	7.8	254	1.52	0.6	2.6	14.2	33	14	70	6	13	18	12
C-2	7.0	9.5	0.82	–	–	11.6	–	11.1	273	1.57	0.9	2.4	11.9	33	16	64	11	13	24	12
C-3	7.0	8.6	0.75	–	–	11.5	–	5.5	253	1.51	2.0	2.1	10.9	32	16	65	11	9	21	14
C-4	6.8	7.5	0.66	–	–	11.3	–	6.4	248	1.48	2.0	2.6	11.5	34	16	68	11	9	19	13
C-5	6.6	10.4	0.93	–	–	11.2	–	1.9	261	1.62	1.2	3.1	13.6	33	14	67	10	9	20	14
C-6	6.4	9.7	0.78	–	–	12.4	–	7.6	271	1.53	1.1	2.6	12.8	34	13	66	10	9	19	15
C-7	7.5	7.0	0.59	–	–	11.9	–	5.1	237	1.42	0.8	3.2	14.0	33	13	66	12	11	23	11
C-8	7.0	6.9	0.62	–	–	11.2	–	5.7	232	1.52	1.0	2.6	12.2	35	16	68	11	6	17	15
C-9	6.9	7.4	0.64	–	–	11.5	–	5.1	250	1.55	1.2	2.5	11.3	33	16	66	12	7	18	16
C-10	6.7	6.3	0.55	–	–	11.4	–	3.5	217	1.52	0.7	2.1	11.7	36	14	66	11	7	18	16
Weekaty, Uncultivated																				
U-1	6.3	13.5	1.02	–	–	13.3	–	5.6	276	1.40	1.2	3.5	12.1	19	15	52	18	15	34	15
U-2	6.4	13.6	1.03	–	–	13.2	–	8.0	319	1.49	2.5	2.8	12.3	21	11	50	17	20	36	14
U-3	6.8	14.0	1.05	–	–	13.3	–	6.6	290	1.52	1.4	2.9	11.4	23	12	52	13	16	29	19
U-4	6.0	13.4	1.08	–	–	12.4	–	6.1	263	1.40	0.6	2.4	13.7	30	15	63	13	11	24	13
U-5	6.2	9.6	0.81	–	–	12.1	–	4.6	236	1.54	0.3	1.7	11.4	34	16	66	13	8	20	12
U-6	6.3	14.9	1.12	–	–	13.2	–	7.0	284	1.52	1.0	4.4	16.3	21	12	54	17	16	33	12
U-7	6.3	32.7	2.23	–	–	14.6	–	13.6	411	1.39	0.6	3.1	7.6	11	7	31	17	28	45	24
U-8	6.9	16.7	1.35	–	–	12.4	–	16.2	375	1.44	1.5	3.0	10.6	22	13	52	13	17	30	18
U-9	6.4	11.3	0.91	–	–	12.3	–	4.4	276	1.42	1.4	1.9	8.5	29	16	60	14	11	25	16
U-10	6.4	8.5	0.74	–	–	11.5	–	5.7	272	1.36	1.4	1.9	12.3	34	15	67	10	9	19	14
Weekaty Mid-field, Cultivated																				
C2-1	6.9	7.2	0.59	–	–	12.3	–	–	–	1.49	1.1	3.0	14.3	34	13	67	9	10	19	14
C2-2	6.9	12.6	1.02	–	–	12.4	–	–	–	1.48	0.6	3.7	14.9	32	14	67	11	10	20	13
C2-3	7.0	15.0	1.24	–	–	12.1	–	–	–	1.57	1.2	2.8	11.3	33	16	67	13	9	22	11
C2-4	7.4	10.9	0.82	–	–	13.4	–	–	–	1.49	0.7	2.5	11.7	33	16	67	13	8	21	12
C2-5	7.5	9.9	0.79	–	–	12.5	–	–	–	1.47	0.8	2.9	13.8	36	16	70	11	9	20	10
C2-6	7.0	6.7	0.59	–	–	11.4	–	–	–	1.53	0.7	1.8	11.6	36	15	66	16	7	23	11
C2-7	7.4	8.3	0.64	–	–	12.9	–	–	–	1.62	0.8	2.8	12.5	31	14	70	11	9	20	10
C2-8	7.4	7.9	0.65	–	–	12.1	–	–	–	1.53	1.2	3.3	15.0	29	16	63	12	10	23	14
C2-9	7.5	11.7	0.85	–	–	13.8	–	–	–	1.53	1.1	2.4	10.7	29	17	62	14	10	24	14
C2-10	6.6	5.7	0.47	–	–	12.3	–	–	–	1.56	2.0	4.5	16.4	36	13	73	8	8	16	10
Sanchez, Cultivated																				
C-1	6.9	23.2	1.61	9.6	17.6	14.4	–	10.2	267	1.61	–	–	–	–	–	24	25	21	46	30
C-2	6.6	24.7	1.69	22.1	17.2	14.6	–	12.6	340	1.55	–	–	–	–	–	23	24	23	47	30
C-3	7.4	24.5	1.05	12.0	13.9	11.5	–	7.2	243	1.80	–	–	–	–	–	24	21	21	42	34
C-4	7.5	10.1	0.91	7.3	12.6	11.1	–	5.6	321	1.74	–	–	–	–	–	31	17	21	38	31
C-5	7.4	9.5	0.80	5.9	15.2	11.9	–	6.3	306	1.63	–	–	–	–	–	42	17	14	31	27
C-6	7.1	13.5	0.83	7.9	15.8	16.2	–	6.9	297	1.63	–	–	–	–	–	38	19	17	36	26
C-7	6.9	22.4	1.54	8.4	20.6	14.5	–	12.1	370	1.59	–	–	–	–	–	36	19	19	36	26
C-8	6.9	16.8	1.42	9.5	16.5	13.3	–	9.5	207	1.58	–	–	–	–	–	29	20	22	42	29
C-9	7.1	10.6	0.96	7.6	11.6	11.1	–	6.2	246	1.66	–	–	–	–	–	29	20	20	40	31
C-10	7.1	9.1	0.80	5.4	10.4	11.4	–	5.6	366	1.75	–	–	–	–	–	38	19	16	35	27
Sanchez, Uncultivated																				
U-1	7.0	13.6	0.95	3.9	9.3	14.3	–	6.0	212	1.43	–	–	–	–	–	56	16	12	28	17
U-2	7.0	6.2	0.45	1.4	7.7	13.7	–	5.7	237	1.56	–	–	–	–	–	69	12	9	21	10
U-3	6.8	17.2	1.03	3.8	11.7	16.7	–	6.5	216	1.46	–	–	–	–	–	44	26	14	40	16
U-4	6.4	26.8	1.92	24.2	14.1	14.0	–	11.3	243	1.28	–	–	–	–	–	33	26	22	48	19
U-5	6.9	8.1	0.67	1.3	7.5	12.1	–	5.6	174	1.55	–	–	–	–	–	50	16	15	31	19
U-6	6.9	7.9	0.57	1.1	8.0	13.9	–	9.6	247	1.63	–	–	–	–	–	76	10	5	15	9
U-7	7.0	13.7	0.91	3.7	10.2	15.0	–	7.9	192	1.52	–	–	–	–	–	56	16	10	28	16
U-8	6.7	12.9	0.88	4.4	10.5	13.4	–	8.3	201	1.42	–	–	–	–	–	53	14	15	29	18
U-9	6.9	11.3	0.95	3.9	12.1	11.9	–	5.8	153	1.57	–	–	–	–	–	56	11	12	23	21
U-10	6.9	8.9	0.76	1.7	10.9	11.7	–	6.9	173	1.47	–	–	–	–	–	58	14	12	26	16

Chemical and Physical Soil Data for Intensive (Paired) Profiles

Field and Soil Horizon	Depth (cm)	pH	Org C (g/kg)	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	C:N Ratio	Inorg. C (g/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
B. Laste, Intensive Cultivated, Profile																					
Ap	0-23	7.5	11.1	0.71	--	--	14.7	0.58	8.8	464	1.61	0.0	0.3	2.2	21	19	42	17	16	33	25
2C1	23-37, sandy	7.8	7.1	0.47	--	--	13.5	0.70	5.4	809	1.46	0.0	0.3	3.6	29	21	53	14	12	26	21
2C1	23-37, silty	7.7	12.8	0.71	--	--	16.8	0.85	5.4	412	1.34	0.0	0.1	0.9	5	9	15	22	34	56	29
2C2	37-68	7.7	8.9	0.61	--	--	13.5	0.65	5.4	780	1.48	0.0	0.1	3.1	19	11	34	11	24	36	31
3C3	68-96, sandy	7.8	10.2	0.81	--	--	15.3	0.84	4.3	782	1.40	0.1	1.0	6.8	36	17	61	9	11	20	19
3C3	68-96, silty	7.8	5.3	0.29	--	--	14.9	0.94	4.2	477	1.49	0.0	0.0	0.6	9	9	19	19	32	51	30
4Btb	96-119	7.6	7.0	0.65	--	--	10.7	0.11	6.1	437	1.69	0.0	0.0	0.8	10	10	21	13	24	37	42
4Btkb	119-140	7.8	10.0	0.67	--	--	12.9	1.46	7.5	483	1.62	0.0	0.2	1.9	12	12	26	17	30	47	27
4BCtkb	140-150	7.8	13.1	0.67	--	--	16.0	2.49	8.8	571	1.36	0.1	0.1	0.6	2	11	14	25	21	47	39
Auger	275-290	7.6	8.7	0.65	--	--	12.4	0.66	7.3	536	–	0.0	0.0	0.1	1	2	1	13	31	44	55
B. Laste, Intensive Uncultivated, Profile																					
A	0-17	7.7	15.8	0.86	--	--	17.8	0.46	9.3	453	1.35	0.0	0.1	0.7	14	23	38	21	15	36	28
2C1	17-40, sandy	8.0	3.1	0.27	--	--	9.5	0.63	4.0	347	1.43	0.0	0.4	10.9	53	11	75	5	8	12	13
2C1	17-40, silty	7.8	14.9	0.76	--	--	18.6	0.85	6.2	470	1.36	0.0	0.0	0.3	1	2	3	19	68	87	10
3C2	40-80	7.8	14.1	0.91	--	--	14.6	0.96	8.3	526	1.40	0.0	0.1	1.0	7	9	18	26	30	56	26
4C3	80-107	7.9	9.0	0.59	--	--	13.9	0.79	6.0	383	1.29	0.0	0.1	0.2	14	28	42	16	17	33	25
5Btb	107-126	7.6	8.4	0.80	--	--	10.3	0.11	13.1	482	1.55	0.0	0.0	0.4	7	10	17	15	25	40	43
5Btkb	126-150	7.7	7.9	0.74	--	--	9.9	0.62	9.6	461	1.70	0.0	0.0	0.3	9	8	17	12	25	37	46
Auger	280-290	7.6	8.6	0.60	--	--	13.7	0.33	7.3	465	--	0.0	0.2	1.8	12	14	29	11	21	33	39
B. Laste, Above Cornfield																					
A	0-11	7.5	8.5	0.77	--	--	10.9	0	11.6	388	1.36	0.6	1.4	6.4	36	13	57	12	10	22	20
AC	11-19	8.0	8.1	0.77	--	--	10.5	0	4.2	403	1.56	0.3	1.4	4.9	27	10	44	16	13	29	26
C	19-30	8.2	5.6	0.51	--	--	10.9	0	2.2	403	1.49	0.2	1.2	4.8	32	14	53	11	12	23	24
2AC1	30-49	8.2	5.3	0.48	--	--	11.6	0	3.3	295	1.53	0.6	3.6	8.6	36	9	59	11	11	21	20
2AC2	49-62	8.2	5.0	0.44	--	--	11.3	0	3.8	345	1.47	1.1	4.8	12.0	37	8	70	2	9	12	18
3Ab1	62-72	8.2	6.4	0.51	--	--	12.5	0	4.0	464	1.59	1.4	3.9	8.7	27	10	53	10	13	22	25
3Ab2 & 3ABtb	72-86	8.2	6.5	0.70	--	--	8.3	0	4.9	365	1.49	0.8	2.2	5.4	23	12	44	14	14	28	28
3Btb	86-96	8.1	7.9	0.69	--	--	11.5	0	2.0	281	1.75	0.2	0.9	2.5	16	13	33	16	16	32	35
3Btkb1	96-115	8.2	9.6	0.63	--	--	15.3	0	2.8	287	1.66	0.8	1.7	3.5	17	14	37	14	17	32	31
3Btkb2	115-150	8.3	9.1	0.62	--	--	14.6	0	2.3	283	1.65	0.2	0.9	2.6	16	9	30	15	23	36	32
3BCtkb	245-300	8.2	--	--	--	--	--	--	--	--	--	0.9	1.5	3.5	21	10	38	14	16	32	30
Wekoety, Intensive Cultivated, Profile																					
Ap	0-17	6.8	6.7	0.76	--	--	11.5	0	8.6	237	1.46	1.4	2.8	12.3	35	16	69	9	10	19	12
ABt	17-28	6.6	6.1	0.61	--	--	10.0	0	2.8	216	1.55	1.1	2.3	11.1	36	17	55	19	14	33	12
Bt max	28-40	6.7	6.7	0.63	--	--	10.7	0	2.7	283	1.50	2.2	2.7	10.0	32	14	61	13	9	22	17
Bt	28-68	6.8	5.8	0.54	--	--	10.7	0	2.7	223	1.46	0.8	1.8	9.4	34	15	58	15	11	26	16
Bt or BCt	68-81	7.0	3.8	0.37	--	--	10.3	0	2.4	194	1.46	1.5	2.7	12.3	36	16	67	12	9	22	12
Bt or BCt	81-105	7.6	6.5	0.48	--	--	13.4	0	2.4	206	1.40	0.5	0.6	4.6	31	20	56	11	15	26	18
2Btk1	105-141	7.8	6.7	0.59	--	--	14.9	0	2.2	247	1.54	0.3	1.0	8.2	17	9	34	9	23	33	33
2 or 3Btk2	141-150	7.8	6.0	0.40	--	--	15.0	0	3.0	191	1.46	1.1	3.1	14.1	35	15	68	10	9	19	13
Auger	270-300	7.6	6.9	0.34	--	--	20.1	0	4.3	204	–	0.7	1.0	5.7	25	25	57	12	13	25	18
Wekoety, Intensive Uncultivated, Profile																					
A	0-9	6.4	22.7	1.63	--	--	14.0	0	13.0	412	1.46	0.0	2.6	10.8	21	12	47	14	23	37	16
BAt	9-27	6.6	11.2	0.73	--	--	15.3	0	5.7	268	1.50	0.5	2.0	10.8	26	14	52	16	16	33	16
Bt1	27-59	6.7	8.0	0.59	--	--	13.4	0	2.7	255	1.58	0.5	1.7	8.2	25	13	51	11	18	28	21
Bt2	59-82	6.7	5.9	0.49	--	--	11.9	0	1.7	227	1.63	0.4	0.5	4.4	25	19	49	13	14	26	24
BCt1	82-101	6.7	5.9	0.47	--	--	12.7	0	1.7	215	1.52	1.2	2.7	13.5	26	11	58	5	14	19	23
BCt2	101-132	7.0	5.8	0.44	--	--	13.1	0	2.0	224	1.46	0.5	1.2	7.4	27	19	55	11	12	24	21
BCt3	132-150	7.7	4.7	0.33	--	--	14.4	0	2.0	186	1.49	0.3	1.5	10.1	38	17	67	6	10	18	15
Auger	275-300	6.6	7.3	0.43	--	--	17.1	0	3.5	228	--	0.1	0.4	1.6	9	14	25	17	25	42	33
Sanchez, Cultivated																					
Ap	0-23	7.1	18.6	1.46	8.1	41.1	12.8	0	9.1	302	1.54	0.4	0.8	2.7	6	11	24	22	24	46	30
Bw	23-30	7.8	8.2	0.76	1.2	0	10.9	0	2.6	177	1.56	0.2	0.3	0.6	6	15	22	20	24	44	34
Bk1	30-46	8.1	8.5	0.68	1.2	12.2	12.7	0	2.9	326	1.54	1.4	2.3	4.0	7	9	24	24	22	46	30
2Bk2	46-61	8.1	5.5	0.52	1.5	0	10.7	0	3.2	165	1.54	3.7	6.5	11.9	20	12	54	14	14	28	18
2Bk3	61-86	8.1	6.2	0.53	0	0	11.8	0	3.1	331	1.53	1.2	3.9	11.8	25	15	57	11	11	22	21
37Btkb1	86-97	8.0	4.6	0.52	0	7.2	8.9	0	3.5	230	1.71	–	–	–	–	–	59	8	11	19	22
37Btkb2	97-113	8.0	4.3	0.59	0	7.3	7.3	0	3.5	300	1.70	–	–	–	–	–	56	9	12	21	24
4ABtkb	113-156	8.2	6.9	0.70	0	7.4	9.9	0	4.5	267	1.53	–	–	–	–	–	47	14	12	26	27
Auger	300-310	8.2	3.2	0.34	0	4.9	8.6	0	6.1	311	--	–	–	–	–	–	68	9	9	18	14
Sanchez, Uncultivated																					
A	0-7	6.4	17.6	1.15	11.5	18.8	15.3	0	15.9	260	1.38	–	–	–	–	–	66	14	9	23	11
BA	7-16	6.9	11.7	0.98	0	12.0	11.8	0	4.5	232	1.61	–	–	–	–	–	37	15	19	34	29
Bt	16-47	7.1	11.1	0.80	0	10.0	12.3	0	3.0	314	1.67	–	–	–	–	–	28	13	21	34	38
Btk1	47-65	7.8	11.4	0.77	0	9.5	14.7	0	30.0	210	1.53	–	–	–	–	–	30	16	20	36	34
2Btk2	65-77	7.9	9.7	0.61	1.1	8.4	15.9	0	3.7	228	1.57	–	–	–	–	–	48	8	16	24	28
2BC	77-116 (coarse)	7.5	6.7	0.43	0	7.8	15.5	0	4.9	267	1.61	–	–	–	–	–	58	8	13	21	21
2BC	77-116 (fine)	7.8	6.9	0.48	0	6.4	14.5	0	4.7	233	1.56	–	–	–	–	–	57	7	13	20	23
3C1	116-135	7.6	8.4	0.55	0	7.0	15.3	0	4.3	356	1.46	–	–	–	–	–	48	12	14	26	26
4C2	135-155 C	7.6	5.5	0.37	0	6.7	14.7	0	4.8	209	1.63	–	–	–	–	–	62	7	11	18	20
5Ab	134-155 Ab	7.8	9.9	0.78	0	8.1	12.7	0	4.8	422	1.70	–	–	–	–	–	22	18	23	42	36
Auger	285-300	7.8	12.7	0.53	4.2	4.3	24.2	0	6.2	125	--	–	–	–	–	–	65	9	9	18	17

Chemical and Physical Soil Data for Extensive (Unpaired) Transects

Field	Sampling Point	pH	Org C (g/kg)	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	C:N Ratio	Inorg. C	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
Nutria Cultivated Fields																					
NC1	C1	6.8	4.7	0.46	–	–	10.2	–	8.0	304	1.41	0.2	1.8	13.3	38	15	70	9	9	18	12
Peyretea	C2	7.0	10.2	0.88	–	–	11.6	–	13.1	326	1.38	0.2	1.9	11.4	36	13	63	12	7	20	17
	C3	7.3	5.6	0.57	–	–	9.8	–	13.0	256	1.54	0.6	2.2	12.3	37	14	67	8	11	19	14
	C4	7.3	6.2	0.61	–	–	10.3	–	15.1	314	1.57	0.5	2.6	17.9	36	12	70	8	7	16	14
	C5	7.1	10.2	0.86	–	–	10.6	–	21.1	308	1.41	0.4	2.6	22.1	36	7	69	9	8	16	15
	C6	7.0	5.7	0.58	–	–	9.6	–	10.0	311	1.43	0.2	1.6	10.7	38	8	69	12	8	18	13
	C7	7.1	5.0	0.55	–	–	9.1	–	9.5	237	1.52	0.3	1.2	8.3	43	8	71	8	7	16	13
	C8	7.4	5.1	0.51	–	–	10.0	–	16.5	218	1.57	0.5	2.5	14.1	38	13	69	8	8	16	15
	C9	7.6	6.2	0.55	–	–	11.2	–	11.6	246	1.51	0.6	2.9	16.1	30	13	64	11	13	23	13
	C10	6.9	9.6	0.86	–	–	11.1	–	16.6	268	1.47	0.2	2.1	22.0	41	8	74	7	7	13	13
NC2	C1	7.5	8.4	0.52	–	–	16.2	–	4.6	287	1.49	0.7	1.4	10.5	37	12	61	10	11	22	17
Quandalacy	C2	7.4	12.4	0.71	–	–	17.3	–	6.7	287	1.54	0.7	2.1	10.8	27	12	53	14	13	27	20
	C3	7.4	14.4	0.86	–	–	16.4	–	9.6	239	1.54	0.9	1.8	8.4	25	12	49	15	15	30	21
	C4	7.3	21.5	1.20	–	–	17.9	–	9.2	293	1.51	0.2	0.5	1.5	8	11	22	23	25	48	30
	C5	7.4	26.7	1.53	–	–	17.4	–	11.0	327	1.51	0.0	0.3	1.4	7	10	20	23	26	49	31
	C6	7.6	11.1	0.64	–	–	17.4	–	3.8	258	1.51	0.8	2.6	12.4	30	10	57	12	13	25	18
	C7	7.4	20.0	1.10	–	–	18.1	–	6.5	296	1.44	0.2	1.2	3.6	12	13	30	21	23	43	26
	C8	7.5	15.3	0.87	–	–	17.6	–	9.6	366	1.49	0.0	0.9	4.9	19	15	41	19	17	36	23
	C9	7.3	24.9	1.44	–	–	17.3	–	10.1	365	1.50	0.1	0.3	1.1	5	9	16	23	29	52	32
	C10	7.5	24.3	1.37	–	–	17.8	–	12.2	375	1.45	0.2	0.2	1.8	7	11	21	25	26	51	28
NC3	C1	7.7	7.5	0.68	–	–	11.1	–	8.1	289	1.45	0.6	4.3	11.8	37	9	63	11	10	21	16
Simplicio	C2	7.7	6.5	0.62	–	–	10.5	–	5.7	317	1.44	0.8	4.3	11.4	34	11	62	11	11	22	15
	C3	7.5	7.5	0.70	–	–	10.8	–	7.8	315	1.35	1.3	3.9	11.1	37	11	65	11	9	20	15
	C4	7.7	6.5	0.63	–	–	10.2	–	5.0	319	1.41	1.2	2.9	9.4	36	13	62	12	11	23	15
	C5	7.6	6.9	0.65	–	–	10.7	–	8.3	286	1.36	2.0	4.7	13.5	38	8	68	10	9	19	13
	C6	7.8	6.0	0.58	–	–	10.3	–	4.9	271	1.43	2.0	4.0	11.9	[illegible]	10	66	10	10	20	16
	C7	7.8	6.0	0.57	–	–	10.5	–	3.2	365	1.34	1.8	3.9	11.6	38	9	66	10	10	20	14
	C8	7.8	7.7	0.71	–	–	10.8	–	4.3	272	1.40	0.3	3.2	10.2	37	11	63	11	11	22	15
	C9	7.7	7.1	0.64	–	–	11.2	–	5.1	256	1.44	2.4	4.9	12.8	38	9	66	8	10	19	16
	C10	7.6	6.3	0.62	–	–	10.0	–	5.7	320	1.42	0.9	4.1	12.9	42	8	68	10	8	18	13
Nutria Abandoned Fields																					
NA1	A1	7.2	14.2	1.10	–	–	12.9	–	16.5	298	1.52	0.1	0.6	5.2	17	9	32	17	21	38	30
Chimeni	A2	7.3	16.7	1.21	–	–	13.8	–	14.7	317	1.40	0.0	0.6	4.1	13	7	25	19	27	46	29
	A3	7.2	15.1	1.08	–	–	14.0	–	13.5	310	1.47	0.2	0.7	2.6	9	7	20	20	28	49	31
	A4	7.4	18.5	1.52	–	–	12.8	–	16.7	374	1.48	0.0	0.4	1.7	6	6	15	24	31	55	30
	A5	7.3	16.0	1.23	–	–	13.0	–	17.2	364	1.46	0.3	0.4	2.3	7	5	16	20	30	50	34
	A6	7.1	15.6	1.14	–	–	13.7	–	11.3	275	1.46	0.0	0.4	3.1	13	9	27	22	23	45	28
	A7	7.4	14.6	1.10	–	–	13.2	–	12.5	281	1.40	0.2	0.2	2.8	12	8	24	22	26	48	27
	A8	7.3	16.9	1.34	–	–	14.1	–	16.2	376	1.51	0.1	0.3	1.5	6	7	16	23	30	52	32
	A9	7.3	20.6	1.58	–	–	13.0	–	21.0	410	1.50	0.3	0.6	1.7	6	6	15	25	30	55	30
	A10	7.5	17.3	1.31	–	–	13.2	–	20.0	361	1.53	0.5	0.8	4.5	12	6	25	19	27	46	29
NA2	A1	7.4	6.2	0.53	–	–	11.7	–	6.8	312	1.51	0.7	1.5	4.2	25	20	52	18	11	28	21
	A2	7.1	7.8	0.77	–	–	10.2	–	8.5	294	1.40	0.7	2.5	4.9	15	10	34	20	14	33	33
	A3	6.6	4.1	0.44	–	–	9.3	–	7.8	273	1.59	0.9	4.9	14.0	27	11	58	13	9	22	19
	A4	7.1	8.8	0.81	–	–	10.8	–	13.3	382	1.38	1.3	2.6	6.8	20	10	42	18	19	37	21
	A5	6.8	13.0	1.02	–	–	12.7	–	16.6	370	1.32	1.3	5.7	9.6	16	10	44	22	14	36	20
	A6	7.8	6.9	0.64	–	–	10.7	–	6.3	257	1.44	1.7	2.3	5.5	21	12	44	18	13	30	26
	A7	7.5	8.7	0.77	–	–	11.2	–	9.3	312	1.41	1.0	2.6	6.3	22	13	46	17	12	29	25
	A8	7.6	6.5	0.69	–	–	9.5	–	5.0	299	1.59	1.3	3.2	6.6	16	11	40	13	14	26	33
	A9	7.0	5.5	0.56	–	–	9.7	–	6.0	313	1.49	0.5	0.9	7.2	23	12	45	15	13	29	26
	A10	6.9	6.3	0.65	–	–	9.7	–	12.1	268	1.49	2.4	3.8	10.3	21	9	48	14	13	26	26
NA3	A1	6.4	24.3	2.07	–	–	11.8	–	28.1	312	1.49	0.1	2.1	5.6	14	6	30	18	26	43	27
Laste	A2	6.5	9.0	0.88	–	–	10.5	–	13.1	283	1.53	1.2	3.0	10.3	31	12	58	15	12	26	15
	A3	7.0	6.0	0.59	–	–	10.2	–	12.3	295	1.45	2.1	3.4	12.8	37	12	69	12	8	20	11
	A4	7.2	8.0	0.73	–	–	11.0	–	18.7	316	1.60	0.7	2.1	8.7	31	12	56	14	12	26	18
	A5	6.9	8.2	0.78	–	–	10.5	–	18.9	246	1.51	0.6	2.7	8.9	30	12	56	15	11	26	18
	A6	6.6	27.4	2.12	–	–	12.9	–	23.7	373	1.36	0.0	0.9	2.3	6	7	19	21	30	51	30
	A7	6.4	17.8	1.50	–	–	11.9	–	23.3	318	1.59	0.3	2.1	7.6	24	10	45	14	20	34	21
	A8	7.3	5.4	0.57	–	–	9.4	–	8.0	228	1.57	2.5	4.2	11.3	33	11	64	12	9	21	15
	A9	6.9	12.9	1.08	–	–	11.9	–	20.6	308	1.62	0.6	2.2	7.4	23	11	46	16	15	32	23
	A10	6.7	12.4	1.13	–	–	11.0	–	17.8	368	1.47	0.6	2.0	6.5	18	10	39	18	17	34	27
Nutria Uncultivated Fields				–	–		–													
NU1	U1	7.0	10.7	0.80	–	–	13.4	–	10.6	396	1.58	0.6	1.1	2.5	10	10	25	16	24	40	36
Laste	U2	6.6	14.3	1.02	–	–	14.1	–	13.4	410	1.56	0.2	0.7	2.2	9	9	22	17	26	43	35
	U3	6.8	12.1	0.86	–	–	14.0	–	12.0	414	1.56	0.3	0.5	1.8	10	11	25	23	26	48	26
	U4	7.0	10.3	0.74	–	–	13.9	–	11.5	381	1.52	0.5	1.1	3.7	13	15	30	24	21	45	25
	U5	7.0	13.1	0.93	–	–	14.1	–	8.3	362	1.44	0.7	1.0	3.3	13	15	34	21	22	43	24
	U6	6.9	16.3	1.13	–	–	14.4	–	13.3	383	1.61	0.5	0.6	1.7	6	9	18	22	28	50	32
	U7	7.1	12.5	0.90	–	–	13.9	–	13.1	378	1.29	0.4	0.3	1.2	6	8	16	15	28	44	40
	U8	6.9	15.5	1.12	–	–	13.8	–	12.8	414	1.48	0.1	0.4	1.5	6	8	17	17	28	45	37
	U9	6.8	15.1	1.03	–	–	14.6	–	8.7	363	1.60	0.4	0.8	3.2	10	14	30	22	23	45	26
	U10	6.8	14.4	1.05	–	–	13.7	–	13.5	421	1.45	0.6	2.1	5.8	16	19	44	24	17	40	15
NU2	U1	6.5	18.9	1.40	–	–	14.2	–	16.6	420	1.43	0.1	2.5	8.7	23	11	48	15	19	34	19
Cattle User's	U2	7.4	17.0	1.24	–	–	13.7	–	15.9	387	1.34	0.0	1.5	6.7	18	7	36	12	21	33	30
	U3	7.0	17.6	1.31	–	–	13.6	–	20.2	442	1.56	0.2	1.5	8.2	24	13	47	16	18	34	19
	U4	7.1	17.4	1.21	–	–	14.4	–	14.4	408	1.22	0.0	0.7	8.6	30	13	51	13	16	28	21
	U5	7.7	23.1	1.64	–	–	14.1	–	15.5	442	1.63	0.3	0.6	4.8	17	12	36	16	24	42	23
	U6	7.0	16.3	1.15	–	–	14.2	–	15.3	428	1.38	0.1	0.7	4.8	18	10	34	16	23	38	27
	U7	7.1	20.8	1.60	–	–	13.0	–	20.4	460	1.55	0.3	1.1	6.3	20	10	36	14	20	34	27
	U8	7.2	15.5	1.14	–	–	13.5	–	18.7	405	1.47	0.0	0.8	8.0	30	12	53	13	14	27	20
	U9	7.1	14.3	0.92	–	–	15.6	–	15.1	387	1.21	0.4	1.5	6.7	24	13	47	12	16	28	25
	U10	7.1	21.0	1.41	–	–	14.8	–	14.5	438	1.37	0.2	0.7	5.8	22	13	44	16	17	36	20
NU3	U1	6.4	30.5	2.07	–	–	14.7	–	27.5	436	1.28	0.1	2.5	5.4	24	14	47	11	17	28	24
Bowanna	U2	7.1	12.3	0.76	–	–	16.1	–	11.6	322	1.37	0.4	1.5	5.6	24	16	48	12	16	28	24
	U3	7.3	8.5	0.64	–	–	15.0	–	11.3	280	1.34	0.6	3.0	8.6	24	13	50	9	18	27	22
	U4	7.4	5.3	0.41	–	–	12.9	–	11.2	283	1.46	0.2	1.3	8.8	34	13	56	7	15	22	22
	U5	7.3	5.7	0.42	–	–	13.6	–	10.5	286	1.52	0.7	3.8	13.8	36	12	66	6	10	16	18
	U6	6.6	7.1	0.57	–	–	12.5	–	14.1	304	1.44	1.9	7.0	16.0	34	6	68	3	11	14	17
	U7	7.5	7.0	0.51	–	–	13.6	–	10.3	286	1.34	0.5	2.5	8.6	30	13	56	9	14	23	21
	U8	7.5	6.6	0.48	–	–	13.5	–	8.8	298	1.47	0.2	0.9	4.5	26	18	48	11	15	26	26
	U9	7.6	5.4	0.41	–	–	13.3	–	8.3	270	1.52	0.1	1.0	6.8	34	16	58	8	12	20	22
	U10	7.4	4.7	0.41	–	–	11.4	–	8.2	272	1.48	0.0	1.4	8.7	33	13	58	7	13	20	23

Field	Sampling Point	pH	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	C:N Ratio	Inorg. C (g/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
Pwaando Cultivated Fields				–	–		–													
PC1	C1	6.5	0.76	–	–	13.8	–	8.3	223	1.56	1.2	6.2	18.8	28	11	64	7	13	20	16
M. Eustace	C2	6.4	0.89	–	–	14.1	–	14.1	169	1.53	0.8	4.6	15.6	24	14	60	18	12	28	12
	C3	6.5	0.71	–	–	12.8	–	10.3	160	1.53	1.7	5.2	16.5	25	12	62	15	11	26	12
	C4	5.6	1.47	–	–	14.0	–	23.1	233	1.58	0.5	2.6	8.3	20	16	47	10	21	31	21
	C5	6.0	1.27	–	–	15.0	–	12.8	171	1.55	0.2	5.8	16.1	25	9	57	10	16	26	17
	C6	6.3	0.95	–	–	14.0	–	13.7	241	1.53	1.6	8.8	23.9	25	10	70	6	11	17	13
	C7	6.3	0.94	–	–	13.5	–	8.8	204	1.86	2.3	7.3	20.8	25	9	66	9	11	20	15
	C8	6.3	0.63	–	–	14.1	–	6.2	192	1.59	2.5	6.1	21.0	34	10	67	6	15	21	12
	C9	6.2	0.89	–	–	14.4	–	12.1	210	1.57	1.2	5.8	15.0	28	14	61	7	15	22	16
	C10	6.2	0.98	–	–	15.7	–	12.1	211	1.58	0.7	5.1	20.7	30	11	68	11	7	19	12
PC2	C1	6.8	0.70	–	–	11.2	–	8.9	290	1.64	0.8	1.3	6.8	28	21	58	16	10	26	16
Erisabo	C2	6.8	1.10	–	–	11.5	–	11.8	366	1.64	1.5	2.6	7.8	20	16	60	16	12	28	12
	C3	6.7	1.04	–	–	13.9	–	7.3	301	1.48	2.0	4.8	12.8	30	12	62	15	11	26	12
	C4	6.3	0.85	–	–	13.5	–	11.7	286	1.48	1.1	4.1	16.7	30	15	67	16	9	25	9
	C5	6.7	0.89	–	–	12.7	–	8.7	298	1.65	1.4	4.2	14.8	23	12	56	14	13	28	16
	C6	7.1	0.73	–	–	11.8	–	13.7	288	1.63	1.1	1.9	7.9	33	17	62	16	9	25	13
	C7	7.0	0.84	–	–	11.6	–	7.8	337	1.49	0.8	3.1	11.8	21	11	48	17	16	32	18
	C8	6.0	1.62	–	–	14.7	–	13.1	375	1.47	0.3	2.6	6.7	15	12	40	23	20	42	18
	C9	6.9	1.12	–	–	12.8	–	15.0	318	1.43	0.7	2.7	11.5	21	14	51	19	14	33	16
	C10	7.1	0.87	–	–	11.3	–	12.8	236	1.61	0.9	4.0	15.9	29	12	63	14	10	24	13
PC3	C1	7.8	1.54	–	–	10.0	–	33.5	348	1.51	1.8	4.6	13.7	23	18	61	17	8	25	14
Kenoota	C2	7.0	1.02	–	–	12.2	–	17.3	338	1.50	1.6	3.3	8.7	18	17	50	22	11	33	18
	C3	7.0	0.87	–	–	13.4	–	13.5	300	1.56	1.9	4.6	13.8	25	16	62	16	8	24	14
	C4	6.9	0.61	–	–	13.5	–	10.2	221	1.56	2.6	5.7	19.7	29	13	71	12	7	18	10
	C5	6.6	0.88	–	–	13.3	–	8.6	284	1.43	1.8	5.3	17.8	29	13	67	13	7	20	13
	C6	7.0	0.91	–	–	12.1	–	13.4	292	1.48	2.8	4.6	11.2	20	16	56	17	10	27	18
	C7	7.1	0.84	–	–	12.8	–	13.8	310	1.52	1.4	4.1	13.2	25	18	63	16	8	24	13
	C8	6.8	0.81	–	–	10.7	–	10.3	320	1.56	1.4	4.1	15.9	28	15	66	14	8	22	14
	C9	6.9	0.86	–	–	12.8	–	8.6	325	1.54	1.2	3.4	16.8	31	14	68	13	7	20	13
	C10	6.6	0.56	–	–	11.9	–	6.7	237	1.58	1.5	4.5	21.5	38	13	77	9	4	13	10
Pwaando Abandoned Fields																				
PA1	A1	6.8	1.27	–	–	13.7	–	17.8	373	1.54	0.0	0.9	5.4	12	8	28	19	23	42	30
Haidi	A2	6.8	1.36	–	–	14.5	–	12.8	414	1.62	0.0	0.6	2.3	5	6	14	13	32	46	41
	A3	6.7	2.06	–	–	12.3	–	17.0	483	1.77	0.0	1.1	5.1	9	4	20	13	29	42	38
	A4	6.8	1.51	–	–	11.8	–	17.8	437	1.54	0.1	0.9	6.5	14	7	30	15	27	42	28
	A5	6.8	1.09	–	–	12.5	–	16.2	394	1.33	0.2	0.4	5.1	13	9	28	22	27	49	23
	A6	6.6	1.26	–	–	14.2	–	12.6	396	1.35	0.0	0.9	4.8	11	9	27	19	23	42	31
	A7	6.7	0.93	–	–	13.3	–	11.1	336	1.60	0.5	1.1	8.9	18	9	38	13	20	33	29
	A8	6.8	1.27	–	–	13.1	–	16.8	327	1.59	0.2	0.6	4.9	12	9	26	15	25	40	34
	A9	6.8	1.55	–	–	11.1	–	17.8	344	1.57	0.0	1.1	6.3	14	6	28	14	25	39	33
	A10	6.5	1.44	–	–	12.5	–	17.0	386	1.49	0.0	0.5	4.8	13	6	27	21	27	48	25
PA2	A1	6.7	0.86	–	–	13.0	–	7.0	281	1.50	1.1	2.5	9.7	19	19	49	20	14	33	18
R. Eustace	A2	7.2	0.75	–	–	14.3	–	6.8	340	1.51	2.0	5.2	10.4	16	15	50	20	13	33	17
	A3	7.9	0.86	–	–	13.7	–	6.2	287	1.46	0.7	2.3	9.4	20	15	48	20	14	34	19
	A4	6.9	0.86	–	–	13.6	–	5.7	382	1.43	0.8	2.8	4.0	12	18	38	27	16	42	20
	A5	6.7	0.73	–	–	12.1	–	10.5	278	1.39	0.7	2.9	5.6	11	12	33	28	19	47	20
	A6	7.0	0.57	–	–	11.8	–	4.8	253	1.35	1.3	4.6	11.1	16	14	50	18	13	32	18
	A7	6.7	0.88	–	–	12.4	–	6.5	253	1.57	1.1	3.6	13.5	21	16	55	20	11	31	15
	A8	6.9	0.53	–	–	12.7	–	7.6	241	1.53	1.1	2.5	11.9	28	15	57	17	10	27	16
	A9	6.7	1.12	–	–	13.8	–	11.3	323	1.44	0.6	1.5	12.7	6	12	32	24	23	47	21
	A10	6.5	0.81	–	–	12.6	–	7.4	331	1.48	4.3	8.4	12.5	16	11	51	17	15	32	17
PA3	A1	6.5	1.53	–	–	13.4	–	12.8	332	1.59	0.2	0.7	3.2	13	16	33	21	21	42	25
Lealryo	A2	6.4	1.17	–	–	13.8	–	17.1	320	1.37	0.2	0.5	3.1	12	12	29	23	22	45	26
	A3	6.4	2.28	–	–	12.5	–	18.3	463	1.46	0.1	1.1	3.1	7	4	16	14	30	44	40
	A4	6.3	1.41	–	–	13.4	–	25.8	313	1.56	0.9	5.6	16.3	23	8	54	14	15	29	17
	A5	6.4	1.20	–	–	12.7	–	14.8	301	1.66	0.0	1.7	7.1	18	13	41	19	17	36	23
	A6	6.7	0.94	–	–	13.4	–	8.5	241	1.51	0.3	0.7	3.1	18	17	39	20	17	37	24
	A7	6.5	1.27	–	–	13.4	–	18.9	346	1.57	0.0	0.4	2.1	7	12	22	30	23	53	25
	A8	6.7	2.05	–	–	13.5	–	19.1	405	1.38	0.4	2.6	5.9	12	10	32	21	21	42	26
	A9	6.2	2.11	–	–	13.1	–	18.1	409	1.60	0.1	1.5	3.6	8	5	18	22	32	54	28
	A10	6.3	0.89	–	–	12.0	–	15.7	270	1.56	0.5	6.1	23.8	18	8	57	11	16	26	17
Pwaando Uncultivated Fields																				
PU1	U1	7.0	0.79	–	–	10.7	–	6.4	215	1.64	0.6	2.4	7.1	0	28	37	17	15	32	31
J. Sanchez	U2	7.0	0.88	–	–	10.0	–	8.7	178	1.61	0.3	1.0	4.3	1	22	28	15	14	29	42
	U3	6.8	0.78	–	–	11.2	–	8.2	243	1.60	0.3	1.5	3.6	1	27	33	18	19	37	30
	U4	7.0	1.08	–	–	10.1	–	4.8	213	1.66	0.0	0.7	1.6	6	12	21	16	15	31	48
	U5	7.1	0.82	–	–	10.1	–	6.2	244	1.33	0.0	1.0	2.7	0	24	28	17	19	36	36
	U6	7.0	0.88	–	–	11.4	–	6.1	316	1.57	0.2	1.3	3.8	10	10	25	18	25	43	32
	U7	6.9	1.02	–	–	10.6	–	4.3	388	1.46	0.8	2.1	6.3	5	18	33	11	12	24	43
	U8	6.8	0.83	–	–	11.0	–	6.3	182	1.46	0.1	1.1	2.8	7	13	25	23	23	46	28
	U9	7.0	1.00	–	–	12.2	–	6.1	230	1.53	0.2	0.7	2.2	2	16	21	18	16	34	45
	U10	6.9	0.87	–	–	11.4	–	4.4	306	1.60	0.1	0.1	1.8	11	12	26	17	14	32	43
PU2	U1	6.6	0.79	–	–	11.7	–	5.6	238	1.38	1.7	1.7	6.8	16	22	48	24	11	35	18
R. Eustace	U2	6.7	0.70	–	–	12.4	–	6.3	171	1.42	2.2	2.2	6.9	21	22	55	21	10	31	14
	U3	6.8	0.76	–	–	10.8	–	6.7	207	1.60	2.0	2.0	9.2	20	18	51	21	15	36	13
	U4	7.1	0.80	–	–	11.0	–	5.6	183	1.40	3.4	3.4	7.7	17	18	49	20	11	31	19
	U5	7.0	0.34	–	–	10.1	–	5.1	155	1.57	3.6	3.6	12.0	28	16	63	16	7	22	15
	U6	7.0	0.77	–	–	10.2	–	5.4	221	1.80	3.0	3.0	10.0	22	17	56	16	12	27	17
	U7	6.5	0.71	–	–	10.8	–	6.0	178	1.58	2.8	2.8	11.4	22	20	57	20	11	31	12
	U8	6.9	0.75	–	–	12.2	–	5.5	280	1.36	1.7	1.7	3.2	7	22	35	32	15	47	18
	U9	6.9	0.54	–	–	11.1	–	5.9	180	1.54	5.3	5.3	14.3	18	18	60	19	8	27	18
	U10	7.1	0.44	–	–	10.4	–	5.0	188	1.54	1.1	1.1	3.3	17	34	46	24	11	34	19
PU3	U1	5.9	1.75	–	–	13.1	–	18.8	287	1.30	0.4	1.8	8.7	28	17	56	17	11	28	16
Hnaldo	U2	6.8	1.13	–	–	13.0	–	9.4	230	1.37	0.5	0.9	7.0	29	17	55	19	10	29	16
	U3	6.8	1.13	–	–	14.0	–	12.8	217	1.28	0.3	1.0	6.8	29	22	60	16	9	25	15
	U4	6.6	0.95	–	–	14.1	–	8.2	208	1.30	0.6	1.3	7.1	29	20	59	16	9	25	16
	U5	7.1	0.84	–	–	14.3	–	11.0	172	1.23	1.0	3.9	15.8	34	14	69	9	6	15	16
	U6	6.9	1.32	–	–	15.1	–	12.4	247	1.11	0.8	2.7	8.4	21	14	48	17	13	30	22
	U7	7.0	0.81	–	–	13.1	–	6.6	234	1.35	0.4	1.1	7.6	30	18	57	18	10	28	17
	U8	6.7	1.01	–	–	13.5	–	11.4	254	1.37	0.8	2.7	11.8	32	17	65	14	9	23	12
	U9	6.8	0.94	–	–	13.0	–	9.6	288	1.36	1.1	2.8	12.0	32	16	65	12	8	20	15
	U10	6.3	0.75	–	–	13.8	–	12.8	216	1.28	0.5	3.7	20.5	38	12	75	9	6	14	11

Field	Sampling Point	pH	N (g/kg)	NO3-N	NH4-N	C:N Ratio	Inorg. C (g/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
Bear Canyon Cultivated Fields																				
BC1	C1	7.0	0.57	–	–	10.6	–	4.8	153	1.34	0.6	2.0	8.7	30	14	57	14	10	25	18
Wyaco	C2	7.4	0.81	–	–	13.8	–	6.4	158	1.28	0.4	0.8	6.5	24	14	42	19	15	34	24
	C3	7.5	0.86	–	–	12.9	–	10.3	203	1.37	0.8	2.4	10.7	29	13	57	13	12	24	19
	C4	7.3	0.88	–	–	11.8	–	4.6	180	1.39	0.5	1.9	8.6	29	12	54	13	14	28	20
	C5	8.0	0.55	–	–	11.4	–	2.8	230	1.49	2.5	6.1	16.8	28	9	63	10	11	21	16
	C6	7.1	1.23	–	–	13.1	–	2.6	171	1.36	0.3	1.1	8.5	30	17	58	14	12	28	16
	C7	7.1	0.85	–	–	12.7	–	5.6	188	1.34	0.8	1.8	6.4	22	13	45	17	15	32	23
	C8	7.3	0.75	–	–	12.5	–	4.4	184	1.40	0.3	1.3	11.6	41	16	71	13	6	18	11
	C9	7.2	1.06	–	–	13.4	–	12.0	142	1.47	1.4	2.3	7.0	21	12	48	14	14	28	24
	C10	6.5	0.88	–	–	13.4	–	2.0	138	1.43	1.2	5.0	16.6	35	9	67	12	7	19	16
BC4	C1	7.2	0.83	–	–	14.2	–	4.8	418	1.50	0.3	0.4	3.0	14	10	28	19	21	40	31
Martinez	C2	7.1	0.87	–	–	14.9	–	14.8	378	1.33	0.4	0.8	4.7	16	11	33	19	20	39	28
	C3	7.4	0.97	–	–	15.8	–	9.1	428	1.52	0.5	1.0	4.8	15	6	31	16	21	37	32
	C4	7.2	0.87	–	–	14.8	–	7.8	401	1.52	0.4	1.2	4.9	15	9	30	15	21	36	34
	C5	7.3	0.72	–	–	20.5	–	16.2	348	1.44	0.8	1.3	4.6	20	12	38	18	16	34	27
	C6	7.2	0.97	–	–	14.4	–	5.8	428	1.54	0.3	0.4	2.5	11	6	22	15	28	41	37
	C7	7.2	1.24	–	–	17.1	–	7.3	381	1.58	0.3	0.4	6.5	21	6	36	14	20	34	30
	C8	7.1	0.86	–	–	15.8	–	7.2	396	1.46	0.7	1.4	6.3	19	10	38	17	18	35	28
	C9	7.0	0.88	–	–	15.3	–	8.4	416	1.56	0.8	1.0	5.3	16	7	31	14	21	35	34
BC5	C1	6.8	0.84	–	–	12.7	–	5.9	343	1.46	0.4	0.8	10.1	38	16	66	14	10	24	10
Boyuka	C2	6.8	0.97	–	–	13.3	–	7.8	387	1.45	0.3	0.6	8.5	38	19	66	14	8	22	11
	C3	6.8	0.87	–	–	12.7	–	6.7	388	1.41	0.3	0.5	7.6	35	16	62	15	8	23	15
	C4	6.5	1.74	–	–	14.1	–	7.5	413	1.43	0.3	0.7	7.1	32	21	62	17	9	26	12
	C5	6.7	0.77	–	–	13.1	–	9.1	403	1.42	0.5	0.9	9.4	33	16	63	14	9	23	15
	C6	6.6	1.15	–	–	13.0	–	12.8	409	1.46	0.4	0.6	6.9	32	16	57	20	12	32	11
	C7	6.4	1.13	–	–	13.1	–	8.3	410	1.38	0.5	0.6	6.8	29	15	53	18	13	31	16
	C8	6.6	0.92	–	–	12.7	–	7.3	298	1.31	0.2	0.4	5.6	32	15	54	8	24	30	15
	C9	6.4	1.20	–	–	12.8	–	8.5	425	1.38	0.3	0.6	7.0	28	16	54	20	12	32	13
	C10	6.5	0.78	–	–	13.7	–	6.6	360	1.38	0.4	1.3	13.8	38	15	70	13	8	20	10
Bear Canyon Abandoned Fields																				
BA1	A1	6.4	0.72	–	–	14.3	–	6.8	174	1.56	6.2	7.7	17.0	30	10	72	6	6	16	12
Nilho	A2	6.5	0.58	–	–	12.7	–	5.3	244	1.40	0.4	0.4	2.9	19	19	41	22	16	38	21
	A3	6.3	1.04	–	–	13.0	–	9.8	224	1.34	0.7	2.8	11.9	31	11	57	14	15	29	14
	A4	6.5	1.34	–	–	14.5	–	9.5	181	1.47	3.2	5.3	16.7	28	7	61	9	15	24	15
	A5	6.5	0.82	–	–	14.3	–	4.6	153	1.52	1.4	3.6	17.0	30	9	62	10	14	23	15
	A6	6.0	0.84	–	–	15.1	–	6.1	275	1.31	0.6	0.4	8.3	29	16	55	14	16	29	16
	A7	5.8	0.80	–	–	13.2	–	5.8	234	1.49	1.4	2.7	11.8	33	15	66	14	9	23	12
	A8	6.7	1.18	–	–	13.7	–	8.2	225	1.38	3.3	4.8	14.1	22	7	51	16	16	32	17
	A9	6.6	1.13	–	–	13.3	–	6.3	325	1.29	0.9	0.8	2.7	6	7	19	16	34	50	31
	A10	7.0	0.80	–	–	12.4	–	7.4	266	1.32	1.2	1.0	4.5	15	13	36	22	19	41	24
BA2	A1	7.2	0.81	–	–	13.3	–	5.6	238	1.29	0.7	2.6	13.7	34	14	66	10	10	20	15
Bowannie	A2	7.4	0.98	–	–	13.3	–	11.2	213	1.23	0.9	5.4	19.8	33	8	68	7	10	17	15
	A3	7.1	1.06	–	–	13.8	–	15.0	260	1.40	1.2	7.3	28.1	34	6	76	6	9	13	12
	A4	6.8	1.07	–	–	12.8	–	9.3	252	1.30	0.8	3.6	16.2	32	6	63	10	11	21	16
	A5	6.8	0.78	–	–	12.8	–	6.6	279	1.39	1.0	3.7	14.6	31	11	62	11	10	21	17
	A6	6.5	1.16	–	–	13.0	–	14.1	233	1.44	0.6	1.8	13.5	36	16	68	10	8	18	14
	A7	6.9	0.88	–	–	13.1	–	12.4	294	1.39	1.3	5.8	16.0	23	8	56	12	14	26	17
	A8	7.2	0.81	–	–	12.7	–	13.0	202	1.32	0.7	5.0	20.5	33	10	70	9	8	17	13
	A9	6.9	1.08	–	–	12.5	–	11.5	275	1.38	1.0	4.6	16.6	29	10	61	13	10	24	16
	A10	7.0	0.82	–	–	12.6	–	12.6	206	1.40	0.6	3.7	12.7	34	12	64	12	9	21	15
BA3	A1	6.9	0.72	–	–	10.8	–	7.1	261	1.38	0.6	1.3	7.8	23	14	46	18	17	36	18
Boyuka	A2	6.8	0.73	–	–	10.9	–	8.8	276	1.30	0.4	0.9	8.3	24	15	47	17	17	36	18
	A3	7.2	0.69	–	–	11.3	–	12.8	343	1.28	0.4	1.0	6.5	21	15	44	18	19	36	21
	A4	7.3	0.84	–	–	11.4	–	11.5	232	1.53	0.5	1.2	7.2	23	14	47	17	18	36	18
	A5	7.0	0.83	–	–	12.0	–	6.1	262	1.36	0.6	1.3	6.8	19	12	41	22	20	41	19
	A6	7.3	0.90	–	–	10.9	–	7.4	250	1.31	0.2	0.4	4.2	19	14	38	19	20	39	22
	A7	6.6	0.81	–	–	10.3	–	15.9	248	1.27	0.4	1.6	8.6	26	15	51	18	15	33	16
	A8	7.4	0.87	–	–	10.9	–	8.8	516	1.33	0.4	0.7	5.6	22	14	44	17	19	36	20
	A9	7.4	1.10	–	–	11.0	–	13.3	252	1.42	0.6	0.6	5.1	19	14	40	20	20	39	21
	A10	7.5	0.78	–	–	12.3	–	4.8	202	1.43	0.2	0.4	5.8	23	17	48	19	15	36	17
BA4	C1	6.6	1.38	–	–	13.4	–	3.0	211	1.49	2.2	6.1	25.0	28	8	67	13	9	22	11
Quandelacy	C2	6.5	1.28	–	–	14.3	–	6.8	176	1.53	1.3	4.0	24.7	35	9	76	10	8	18	6
	C3	6.4	1.48	–	–	13.2	–	7.5	248	1.48	0.4	2.9	14.2	29	10	66	9	13	21	13
	C4	6.2	0.83	–	–	14.5	–	5.5	237	1.40	0.9	4.3	18.8	27	8	58	16	13	28	13
	C5	6.5	1.42	–	–	14.0	–	7.1	244	1.47	0.5	2.9	16.6	29	10	51	22	13	35	14
	C6	6.7	1.20	–	–	14.2	–	5.2	228	1.44	1.7	5.2	22.0	23	8	60	18	11	30	11
	C7	6.8	1.30	–	–	13.4	–	3.9	230	1.80	1.4	5.2	25.8	32	8	73	8	8	18	9
	C8	6.3	1.13	–	–	13.9	–	7.4	237	1.28	0.9	3.7	19.5	33	8	67	11	11	22	11
	C9	6.4	0.90	–	–	13.5	–	6.1	286	1.38	0.8	2.7	16.6	28	8	58	15	14	28	14
	C10	6.8	0.83	–	–	13.8	–	6.9	368	1.58	0.7	2.5	15.2	38	10	57	16	16	32	11
Bear Canyon Uncultivated Fields																				
BU1	U1	6.5	0.87	–	–	12.9	–	6.6	346	1.48	0.2	2.5	11.9	0	42	57	15	11	28	17
Weekoty	U2	6.4	1.81	–	–	13.8	–	13.7	471	1.34	0.3	1.7	5.8	11	16	36	20	20	41	24
	U3	6.5	1.11	–	–	13.9	–	23.8	378	1.32	0.6	4.3	10.3	14	18	48	17	17	34	19
	U4	6.3	1.09	–	–	14.1	–	8.3	394	1.38	0.4	3.1	10.1	11	24	48	16	15	34	17
	U5	6.8	2.52	–	–	14.1	–	10.8	446	1.16	0.2	2.0	4.7	0	20	28	12	36	48	25
	U6	6.7	0.91	–	–	12.8	–	11.1	374	1.46	0.7	2.9	12.1	5	38	60	16	10	28	13
	U7	6.4	1.06	–	–	13.0	–	17.8	337	1.41	0.4	2.7	11.8	6	43	68	16	6	24	11
	U8	6.5	1.03	–	–	13.8	–	13.3	362	1.38	0.2	2.8	8.9	0	37	51	19	13	32	18
	U9	6.5	1.13	–	–	13.5	–	12.9	489	1.33	3.1	3.1	7.7	11	19	44	11	28	37	19
	U10	6.4	1.42	–	–	13.2	–	6.2	422	1.29	0.0	1.2	5.6	0	30	38	15	27	41	21
BU2	U1	5.5	0.70	–	–	13.7	–	14.9	378	1.52	1.2	2.2	12.4	33	11	62	14	13	27	12
Quandelacy	U2	5.8	0.70	–	–	13.3	–	14.7	388	1.47	1.3	3.5	16.8	33	11	66	13	11	24	8
	U3	5.8	0.59	–	–	13.4	–	9.8	472	1.54	1.2	4.0	18.7	35	9	68	12	10	22	9
	U4	5.8	0.83	–	–	13.8	–	13.4	417	1.43	0.7	2.2	20.0	38	10	71	10	8	18	11
	U5	5.8	0.79	–	–	13.3	–	10.7	803	1.42	0.6	2.7	17.8	35	12	68	13	7	20	11
	U6	6.3	1.08	–	–	15.1	–	12.8	365	1.40	0.7	3.0	17.4	34	10	66	14	10	24	10
	U7	6.0	0.78	–	–	13.8	–	11.8	379	1.43	0.8	3.8	20.5	38	9	71	12	7	19	10
	U8	6.1	0.72	–	–	13.1	–	10.9	321	1.43	0.6	3.4	20.8	38	8	73	11	7	18	9
	U9	5.8	0.80	–	–	13.2	–	13.9	441	1.49	0.8	2.9	18.0	31	11	63	14	12	26	11
	U10	5.9	0.80	–	–	13.9	–	18.0	484	1.37	0.4	1.8	12.2	28	12	53	17	16	32	16
BU3	U1	6.7	1.97	–	–	19.5	–	18.4	298	1.23	0.3	0.2	0.8	5	13	20	25	25	50	30
Wyaco	U2	6.9	1.03	–	–	15.0	–	14.2	257	1.48	0.3	0.8	4.8	22	17	46	20	13	33	21
	U3	6.9	1.88	–	–	15.4	–	20.5	279	1.38	0.8	0.9	3.7	14	17	36	17	12	29	21
	U4	6.8	1.79	–	–	14.7	–	18.9	339	1.29	0.7	2.6	10.3	23	13	48	11	18	27	24
	U5	6.6	0.63	–	–	11.2	–	23.0	300	1.28	3.8	4.1	10.0	38	17	76	11	4	15	10
	U6	6.7	1.12	–	–	15.8	–	23.6	271	1.37	0.7	1.1	4.8	18	17	40	23	14	37	22
	U7	6.2	1.88	–	–	16.8	–	20.3	447	1.32	0.4	1.6	5.6	11	11	31	22	20	43	26
	U8	7.1	0.98	–	–	15.4	–	25.3	394	1.48	1.3	2.3	10.5	26	14	55	16	10	26	19
	U9	7.1	1.29	–	–	13.1	–	24.1	484	1.49	1.1	2.0	5.3	17	16	48	21	14	35	22
	U10	7.0	1.17	–	–	13.8	–	16.8	483	1.40	0.6	2.6	6.5	33	16	62	13	8	22	17
BU4	C1	6.5	0.70	–	–	8.9	–	16.8	198	1.53	0.5	1.5	8.4	30	12	51	16	10	28	20
Chapito	C2	6.5	0.79	–	–	10.7	–	10.8	184	1.52	0.3	1.3	10.1	33	14	60	18	10	28	12
	C3	6.2	0.81	–	–	10.8	–	5.2	181	1.58	0.3	1.9	16.8	31	12	68	17	10	28	12
	C4	6.2	1.10	–	–	10.5	–	18.2	272	1.36	0.3	1.6	9.3	26	12	48	20	16	36	17
	C5	6.7	0.73	–	–	9.4	–	7.6	338	1.47	1.0	2.5	12.7	37	10	64	15	8	24	12
	C6	6.0	0.73	–	–	9.9	–	4.7	330	1.48	0.4	4.1	18.5	33	11	68	14	7	21	12
	C7	6.2	1.00	–	–	12.7	–	1.5	195	1.48	0.8	6.0	22.1	33	9	73	10	8	18	9
	C8	6.3	0.84	–	–	10.1	–	6.2	198	1.52	0.4	1.7	12.5	27	12	57	11	14	26	17
	C9	6.1	1.06	–	–	10.0	–	14.7	283	1.44	0.4	2.3	14.5	31	11	58	15	13	27	14
	C10	6.7	0.83	–	–	9.8	–	7.1	198	1.48	1.3	4.5	16.6	33	9	60	26	10	36	14

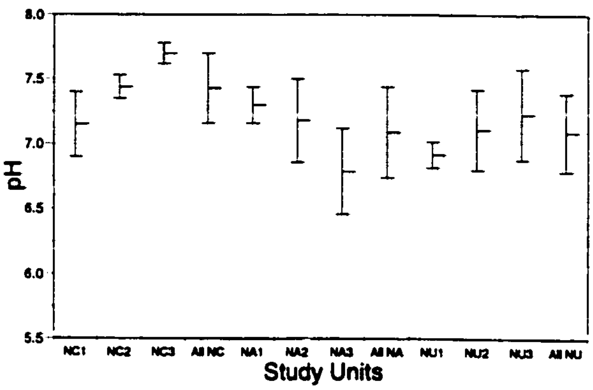
Chemical and Physical Soil Data for Extensive (Unpaired) Profiles

Field	Sampling Point	Depth (cm)	Org C (g/kg)	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	Inorg. C (mg/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
Nutria Study Area																				
NC1	Ap	0-16	5.4	0.54	–	.	.	10.1	378	1.59	0.8	1.6	11.6	40	13	68	9	6	18	18
[illegible]	BAt1	16-30	4.5	0.51	–	–	–	8.8	474	1.52	0.7	1.9	11.9	38	13	66	11	7	18	18
	BAt2	30-57	6.8	0.60	–	–	–	9.8	488	1.44	0.3	1.0	11.3	28	12	53	15	12	28	19
	Bt1	57-70	8.1	0.74	–	–	–	11.0	238	1.59	0.2	0.8	8.8	20	10	41	15	15	31	29
	Bt2	70-91	7.5	0.67	–	–	–	11.1	345	1.61	0.3	0.9	7.1	16	7	32	16	19	35	33
	Btk	91-100	7.0	0.80	–	–	–	11.8	464	1.59	0.4	1.3	8.6	20	10	40	16	14	30	30
	Auger	220-230	4.4	0.33	–	–	–	13.3	240	–	1.9	2.0	9.8	30	10	55	8	11	19	26
NC2	Ap	0-18	17.2	1.02	–	–	–	18.8	475	1.41	0.4	1.3	5.6	20	13	41	19	17	36	24
[illegible]	Bt	18-37	19.8	1.25	–	–	–	15.9	487	1.26	0.3	1.5	5.8	14	10	32	18	23	41	27
	2C1	37-47	9.2	0.61	–	–	–	15.2	368	1.44	0.4	1.5	5.2	30	15	53	15	12	28	20
	3BCtb	47-77	23.8	1.11	–	–	–	21.5	479	1.42	0.1	0.0	0.3	3	15	20	28	25	52	29
	4C2	77-82	3.5	0.37	–	–	–	9.6	347	1.45	0.4	2.6	22.4	43	6	75	5	7	12	13
	Auger	210-220	10.5	0.67	–	–	–	16.7	464	–	0.7	3.3	10.8	37	12	64	11	10	21	16
NC3	Ap	0-18	7.0	0.60	–	–	–	10.2	372	1.52	0.2	0.3	2.1	11	12	28	47	9	56	17
[illegible]	BAt	18-28	7.5	0.78	–	–	–	9.6	395	1.55	0.5	1.3	6.9	29	9	47	12	14	26	26
	Btk1	28-58	6.0	0.67	–	–	–	9.0	381	1.57	0.6	1.4	7.8	33	9	53	11	11	22	25
	Btk2	58-78	6.3	0.58	–	–	–	9.0	348	1.62	0.8	1.8	8.8	36	9	56	11	12	23	21
	BCtk	78-88	6.5	0.48	–	–	–	11.5	366	1.46	0.7	2.9	9.6	32	10	56	11	12	23	21
	Lower C	230-240	4.9	0.40	–	–	–	12.4	350	–	1.3	2.6	8.5	28	11	52	13	14	28	22
NA1	Ap1	0-8	16.9	1.27	–	–	–	13.2	482	1.38	0.4	0.7	3.4	11	9	25	23	25	48	28
[illegible]	Ap2	6-16	15.1	1.07	–	–	–	14.1	483	1.50	0.2	0.8	2.8	6	5	17	18	27	45	37
	Bt	16-38	16.3	1.01	–	–	–	16.1	433	1.51	0.1	0.2	1.2	4	4	11	17	32	48	41
	Btk1	38-62	14.1	0.87	–	–	–	16.1	473	1.51	0.1	-0.1	0.2	3	4	7	16	33	48	44
	Btk2	62-75	13.1	0.81	–	–	–	16.3	381	1.55	0.7	1.0	4.2	13	7	28	17	24	41	31
	Auger	180-200	17.1	0.67	–	–	–	25.7	383	–	0.3	1.0	5.0	24	16	46	11	20	31	22
NA2	Ap	0-13	4.9	0.48	–	–	–	9.8	327	1.52	0.7	2.1	6.6	27	14	51	17	10	27	22
	BAt	13-23	5.9	0.55	–	–	–	10.8	364	1.67	1.0	2.3	7.2	20	7	38	11	16	27	35
	Bt	23-42	7.9	0.66	–	–	–	11.5	433	1.80	0.3	0.7	2.8	8	5	19	14	25	39	42
	Btk	42-75	8.9	0.63	–	–	–	14.2	474	1.78	0.4	0.8	2.0	8	5	17	17	28	44	39
	Auger	200-216	2.8	0.20	–	–		9.6	280	–	2.7	3.8	7.0	29	11	54	8	12	20	26
NA3	Ap	0-10	7.3	0.71	–	–	–	10.3	312	1.55	2.2	4.9	14.0	37	9	68	9	7	16	16
[illegible]	Bw	10-24	3.0	0.38	–	–	–	8.4	247	1.56	1.3	2.7	11.1	42	12	70	8	7	15	15
	C1	24-36	2.7	0.34	–	–	–	7.9	304	1.48	2.1	4.3	13.2	37	12	68	8	8	16	15
	C2	36-42	3.6	0.43	–	–	–	8.4	288	1.42	1.6	3.2	9.6	34	12	61	12	9	22	17
	C3	42-58	3.6	0.44	–	–	–	6.3	284	1.47	0.1	0.3	4.9	37	15	58	12	10	21	20
	C4	58-68	5.4	0.58	–	–	–	9.7	338	1.48	0.2	0.6	5.2	30	13	48	14	14	28	22
	2C5	68-90	3.5	0.43	–	–	–	8.2	325	1.43	0.5	0.7	5.0	17	9	33	13	21	34	34
	Auger	180-180	6.5	0.64	–	–	–	10.2	378	–	2.7	5.1	17.9	34	6	66	6	10	16	18
NU1	A	0-6	14.4	1.05	–	–	–	13.7	533	1.54	0.2	0.4	1.5	8	8	18	20	29	48	35
[illegible]	BA	6-17	12.9	0.97	–	–	–	13.3	524	1.58	0.1	0.1	0.7	4	5	11	17	32	48	40
	Bt	17-68	12.3	0.88	–	–	–	13.9	662	1.57	0.4	0.6	2.4	8	11	24	18	24	41	35
	Btk	68-127	9.6	0.71	–	–	–	13.6	464	1.78	0.8	0.4	2.1	6	7	17	18	27	44	40
	BCtk	127-150	8.0	0.57	–	–	–	14.1	471	1.63	1.3	1.1	3.1	12	9	27	14	26	38	34
	Auger	285-295	17.6	0.63	–	–	–	28.1	443	–	0.2	0.2	1.3	10	15	27	23	22	44	28
NU2	A	0-6	16.3	1.03	–	–	–	14.8	558	1.33	0.1	0.6	5.5	26	15	47	16	17	33	20
Cattle User's	Bt1	6-25	14.0	1.02	–	–	–	13.8	598	1.62	0.1	0.4	4.8	27	15	48	17	15	32	19
	Bt2	25-44	14.7	1.02	–	–	–	14.4	328	1.66	0.5	0.8	8.2	21	8	37	12	20	32	31
	Btk1	44-65	11.4	0.80	–	–	–	14.2	388	1.72	0.2	0.0	1.4	10	7	18	15	28	42	38
	Btk2	65-83	11.9	0.87	–	–	–	13.7	368	1.68	0.5	1.0	6.8	20	9	38	12	19	31	31
	Auger	210-220	11.9	0.51	–	–	–	23.3	348	–	0.2	0.1	1.5	6	4	12	10	34	45	43
NU3	A	0-6	16.3	0.83	–	–	–	18.5	428	1.48	0.5	0.8	8.8	29	11	48	12	25	37	14
[illegible]	AC	6-28	7.0	0.53	–	–	–	13.1	312	1.45	0.8	1.3	3.9	18	15	38	20	36	55	7
	2C1	28-36	3.9	0.38	–	–	–	10.0	326	1.48	0.4	2.3	5.8	31	13	54	10	13	23	23
	3C2	36-43	3.9	0.38	–	–	–	9.8	–	1.43	1.8	6.2	15.8	31	8	63	6	11	17	20
	3C3	43-50	10.2	0.70	–	–	–	14.6	–	1.46	0.5	1.8	15.4	39	8	65	7	10	17	17
	Auger	180-190	4.8	0.41	–	–	–	11.7	–	–	2.1	3.8	11.7	31	10	60	11	11	23	18
Pescado Study Area																				
PC1	Ap	0-21	6.9	0.67	–	–	–	13.3	367	1.55	1.7	7.2	22.0	27	10	68	12	8	20	11
M. Eustace	C1	21-38	3.5	0.35	–	–	–	9.9	218	1.49	3.1	11.6	30.1	31	8	82	4	4	9	9
	C2	38-55	2.3	0.29	–	–	–	8.0	205	–	8.4	20.1	34.8	22	3	89	2	2	4	7
	C3	55-60	2.2	0.24	–	–	–	9.2	188	1.43	7.5	20.4	32.9	20	3	85	4	4	8	7
	2Btb	60-75	7.1	0.49	–	–	–	14.4	275	1.48	0.3	0.9	3.5	15	15	34	27	21	48	18
	2Btkb	75-82	8.0	0.65	–	–	–	12.3	326	1.82	0.8	0.5	3.7	14	8	27	15	22	38	35
	Auger	220-230	6.4	0.43	–	–	–	14.7	370	–	0.4	2.5	18.1	27	10	58	13	11	24	17
PC2	Ap1	0-5	12.0	0.82	–	–	–	13.0	380	1.53	1.1	3.2	10.2	23	11	48	15	14	29	21
[illegible]	Ap2	5-17	10.6	0.72	–	–	–	14.6	338	1.80	0.9	2.1	9.6	28	8	48	14	15	28	24
	Bt1	17-62	8.7	0.73	–	–	–	13.2	327	1.44	0.5	1.0	4.6	10	6	23	18	29	46	32
	Bt2	62-75	8.5	0.57	–	–	–	15.0	300	1.72	0.8	2.2	10.1	24	10	48	13	14	27	26
	Auger	215-225	6.6	0.43	–	–	–	15.8	382	–	0.1	0.4	1.4	7	9	18	21	27	48	32
PC3	Ap1	0-7	9.8	0.78	–	–	–	12.8	313	1.53	2.6	6.2	19.2	28	14	68	13	7	20	11
[illegible]	Ap2	7-15	10.9	0.84	–	–	–	13.0	382	1.52	1.9	5.6	17.2	28	14	66	12	8	20	15
	Bt1	15-52	6.5	0.47	–	–	–	13.8	311	1.63	1.2	4.3	18.2	28	14	66	11	7	18	18
	Bt2	52-77	6.5	0.57	–	–	–	11.4	374	1.55	1.5	4.1	15.8	25	13	61	13	8	21	19
	Auger	180-190	5.4	0.36	–	–	–	15.2	368	–	3.0	4.6	19.4	31	9	67	9	7	16	17
PA1	Ap	0-11	17.7	1.29	–	–	–	13.7	475	1.51	0.0	0.6	4.0	10	5	19	14	28	41	40
[illegible]	BA	11-20	7.6	0.74	–	–	–	10.3	336	1.71	0.2	1.1	9.8	28	10	48	13	15	28	25
	Bt	20-61	8.4	0.64	–	–	–	10.0	334	1.68	0.7	1.5	5.7	14	8	31	17	20	37	32
	Btk	61-75	6.8	0.56	–	–	–	10.5	365	1.51	0.4	1.0	6.0	13	10	32	18	24	43	26
	Auger	170-180	5.2	0.34	–	–	–	15.4	319	–	0.1	0.1	2.0	32	20	55	18	9	25	20
PA2	Ap	0-13	9.4	0.68	–	–	–	13.7	377	1.53	4.1	6.8	16.2	17	9	56	17	9	26	18
R. Eustace	BAt	13-33	6.4	0.51	–	–	–	12.5	324	1.57	1.6	2.6	9.2	30	15	59	16	6	24	17
	C	33-57	5.5	0.46	–	–	–	12.2	338	1.58	0.3	1.5	8.4	27	17	56	17	9	26	18
	2Bt	57-75	7.7	0.68	–	–	–	11.5	447	1.72	0.5	1.1	4.7	11	10	28	8	19	28	34
	Lower C	200-210	1.8	0.31	–	–	–	6.7	410	–	1.4	2.6	7.2	18	10	40	15	14	29	31
PA3	Ap1	0-5	25.8	1.82	–	–	–	13.4	640	1.31	0.4	2.0	4.2	8	5	20	33	22	56	24
[illegible]	Ap2	5-14	13.1	0.92	–	–	–	14.2	388	1.64	0.2	1.0	4.7	17	12	36	25	13	37	28
	Bt1	14-43	9.3	0.72	–	–	–	13.0	380	1.58	0.4	1.1	5.6	18	11	37	22	18	38	23
	Bt2	43-77	9.9	0.73	–	–	–	12.2	413	1.88	1.0	2.8	9.3	17	8	39	18	15	32	29
	Auger	110-120	1.5	0.25	–	–	–	6.6	230	–	3.4	16.9	37.1	23	3	84	3	3	7	8
PU1	A	0-9	10.7	0.88	–	–	–	12.1	213	1.45	0.8	1.2	5.1	18	12	38	22	10	41	24
J. Sanchez	BAt	9-14	9.9	0.90	–	–	–	11.0	380	1.78	0.8	0.8	4.1	13	8	27	15	13	29	44
	Bt1	14-40	10.0	0.75	–	–	–	13.2	317	1.80	0.2	0.3	1.8	8	10	22	18	15	33	45
	Bt2	40-60	9.0	0.61	–	–	–	14.8	270	1.75	0.1	0.2	1.1	13	13	28	19	18	37	35
	Btk	60-71	9.4	0.54	–	–	–	17.5	288	1.62	0.1	0.5	2.8	13	9	27	28	20	48	27
	2ABtkb1	71-88	13.6	0.51	–	–	–	28.6	210	1.43	0.6	1.3	9.5	32	15	59	13	11	23	17
	2ABtkb2	88-118	9.6	0.37	–	–	–	25.8	238	1.48	0.3	1.1	9.3	28	12	50	13	8	21	20
	2ABtb	118-142	14.9	0.54	–	–	–	27.7	248	1.53	0.1	0.2	1.2	8	10	21	22	28	50	29
	2Btb	142-147	11.1	0.56	–	–	–	20.1	294	1.56	0.2	0.2	0.4	4	5	11	18	32	48	41
	Auger	236-246	7.1	0.34	–	–	–	20.8	220	–	0.2	0.2	4.7	32	20	58	14	9	23	20
PU2	A	0-9	7.3	0.68	–	–	–	11.2	288	1.49	0.6	2.3	10.1	21	20	55	18	14	30	12
R. Eustace	BAt	9-28	7.8	0.70	–	–	–	11.1	325	1.48	0.5	1.8	7.0	13	11	33	18	21	40	27
	Bt	28-60	7.1	0.68	–	–	–	10.8	688	1.73	0.8	2.1	7.9	17	15	43	14	10	24	33
	Btk	60-88	7.1	0.48	–	–	–	18.7	248	1.63	1.0	1.3	3.3	5	10	20	22	28	48	34
	2BCtk	88-137	3.2	0.22	–	–	–	14.4	380	1.53	2.9	5.0	19.0	27	15	68	4	12	16	16
	2C	137-180	1.4	0.17	–	–	–	8.2	188	1.49	1.1	5.1	33.5	34	8	88	5	4	9	8
	Auger	275-280	1.0	0.18	–	–	–	4.9	316	–	2.7	3.9	13.5	24	14	58	12	7	19	22

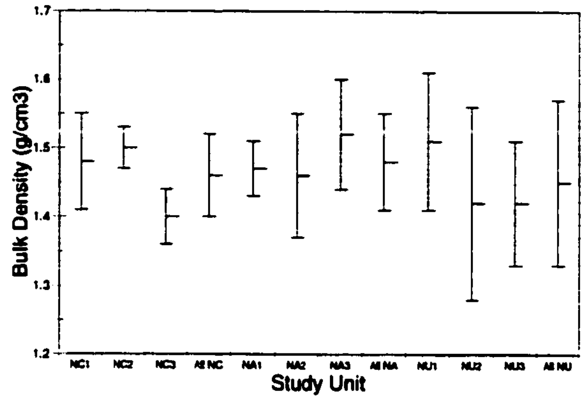
Field	Sampling Point	Depth (cm)	Org C (g/kg)	N (g/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)	Inorg. C (g/kg)	Av P (mg/kg)	Total P (mg/kg)	Bulk Dens. (g/cm3)	VCS (%)	CS (%)	MS (%)	FS (%)	VFS (%)	Sand (%)	Co. Silt (%)	Fn. Silt (%)	Silt (%)	Clay (%)
PU3	A1	0-8	12.2	0.80	–	–	–	12.7	287	1.32	0.5	1.8	8.2	30	16	67	14	6	20	13
Hoskie	A2	8-16	12.0	0.73	–	–	–	16.4	312	1.43	0.0	0.8	5.1	33	18	60	13	9	22	18
	BA	16-22	17.8	1.28	–	–	–	14.0	365	1.26	0.1	0.3	2.0	9	10	22	16	26	42	36
	Bt	22-38	16.0	1.08	–	–	–	14.7	401	1.29	0.0	0.0	0.8	8	9	19	24	21	46	36
	2C1	38-68	11.0	0.68	–	–	–	19.8	328	1.46	0.4	1.8	10.7	34	17	65	-12	29	17	17
	3C2	68-74	8.7	0.40	–	–	–	21.7	340	–	5.1	10.2	28.7	29	5	78	5	4	9	13
	4C3	74-84	6.0	0.40	–	–	–	16.1	253	1.38	0.5	4.8	18.4	36	12	72	8	5	13	15
	Auger	210-226	11.5	0.91	–	–	–	12.6	280	–	0.4	2.0	7.8	23	19	53	17	11	28	19
Bear Canyon Study Area					–	–	–													
BC1	Ap	0-33	14.2	0.79	–	–	–	17.9	188	1.36	0.8	2.1	10.1	31	11	56	12	13	25	19
Wyaco	BA	33-58	12.4	0.73	–	–	–	17.1	227	1.54	0.6	1.6	6.6	32	16	58	13	11	24	17
	Bwt	58-75	7.3	0.34	–	–	–	21.5	179	1.46	1.0	2.9	14.3	44	11	76	7	7	13	12
	2Bw2	75-87	3.5	0.21	–	–	–	16.8	188	1.41	6.5	8.3	20.7	38	8	81	5	5	10	10
	3Btb	87-108	6.5	0.50	–	–	–	12.9	222	1.57	1.1	2.1	8.4	23	12	47	13	15	28	25
	3Btk	108-118	6.9	0.48	–	–	–	14.3	202	1.53	1.7	3.3	7.5	19	11	43	16	16	31	26
	Auger	180-200	7.3	0.47	–	–	–	16.7	307	–	1.6	1.1	6.6	22	9	40	14	17	31	30
BC2	A	0-7	12.7	0.95	–	–	–	13.4	217	–	0.4	8.2	34.9	27	4	76	8	9	15	9
Chapito	Ap	7-18	9.3	0.80	–	–	–	13.4	194	1.57	0.2	1.5	11.8	32	8	54	12	14	27	19
	BAt	18-31	10.1	0.75	–	–	–	13.5	226	1.81	0.4	1.5	10.7	26	7	45	14	17	31	24
	Bt1	31-54	11.4	0.83	–	–	–	13.7	286	1.67	0.3	1.0	5.8	14	7	29	14	21	35	36
	Bt2	54-80	8.2	0.67	–	–	–	13.7	283	1.82	0.2	0.7	4.9	19	9	34	18	16	34	32
	Auger	210-225	5.9	0.29	–	–	–	20.0	240	–	0.5	2.0	14.8	42	10	70	9	8	17	13
BC3	Ap	0-13	11.2	0.78	–	–	–	14.7	329	1.46	0.8	5.2	22.3	36	8	70	9	9	18	11
Quandelacy	BAt	13-29	10.0	0.68	–	–	–	14.4	224	1.48	0.8	4.0	16.9	29	9	60	7	15	25	15
	Bt1	29-60	10.3	0.65	–	–	–	16.0	233	1.36	0.2	2.3	9.3	29	12	54	14	13	28	19
	Bt2	60-68	11.5	0.83	–	–	–	18.2	286	1.28	0.7	2.6	10.8	36	9	51	13	16	29	20
	Bt3	68-80	6.5	0.40	–	–	–	16.1	177	1.30	1.1	5.2	18.7	36	7	68	8	9	18	14
	Auger	210-220	1.8	0.13	–	–	–	13.6	161	–	4.8	12.9	35.0	29	2	84	2	5	7	9
BC4	Ap	0-16	11.4	0.80	–	–	–	13.0	280	1.58	0.8	1.8	6.4	19	8	37	14	18	33	30
Martinez	BAt	16-25	5.8	0.46	–	–	–	12.7	298	1.58	3.1	4.3	11.9	28	8	50	9	11	20	23
	Bt	25-38	4.0	0.34	–	–	–	11.7	284	1.40	0.9	3.2	20.6	36	7	67	6	8	14	19
	2Btb1	38-61	11.0	0.73	–	–	–	15.0	368	1.46	0.2	0.2	1.2	10	12	24	19	33	52	24
	2Btb2	61-75	11.0	0.84	–	–	–	13.1	388	1.51	0.2	0.3	1.7	12	8	23	19	26	44	33
BC5	Ap	0-17	10.1	0.87	–	–	–	11.7	324	1.40	0.2	0.9	8.5	27	24	61	15	11	6	14
Boyuka	BAt	17-31	6.1	0.60	–	–	–	12.1	362	1.57	0.2	0.8	10.2	33	22	66	12	9	20	14
	CB	31-44	4.1	0.31	–	–	–	13.1	317	1.48	0.2	0.8	10.3	38	23	73	6	6	12	15
	2Btb	44-73	5.5	0.36	–	–	–	16.0	238	1.60	0.0	0.3	1.8	8	10	19	15	26	26	40
	3BAtb	73-90	6.6	0.73	–	–	–	13.1	386	1.61	0.0	0.0	1.7	11	24	77	5	4	9	14
	lower Bt	215-225	6.1	0.37	–	–	–	16.3	319	–	0.0	0.7	12.6	33	21	67	6	10	16	17
	Auger	225-236	4.8	0.38	–	–	–	18.8	253	–	0.0	0.0	2.3	16	17	36	12	21	33	32
BA1	Ap	0-8	18.2	1.04	–	–	–	15.6	338	1.46	3.1	5.1	8.2	27	12	20	28	29	56	25
Nilho	Bt1	8-23	6.1	0.44	–	–	–	13.9	188	1.54	0.2	1.3	4.6	30	8	52	18	13	29	19
	Bt2	23-33	6.1	0.40	–	–	–	15.2	186	1.54	0.5	1.5	8.1	28	13	50	17	14	31	20
	2C1	33-50	5.0	0.33	–	–	–	16.3	208		0.7	1.3	2.1	6	8	60	13	10	23	17
	3C2	50-58	1.4	0.17	–	–	–	8.3	238	1.46	0.6	1.4	7.0	28	12	86	4	3	7	7
	4C3	58-68	8.4	0.52	–	–	–	17.9	242	1.38	0.2	1.2	8.6	36	14	21	33	22	56	24
	5C4	68-77	5.8	0.39	–	–	–	15.2	223	1.51	0.8	3.5	23.7	8	8	50	18	11	29	15
	6C5	77-82	11.7	0.78	–	–	–	14.8	325	1.40	0.1	0.1	0.4	4	15	18	19	31	50	32
	Auger	220-230	8.9	0.40	–	–	–	14.8	222		0.1	0.3	1.3	6	7	53	7	18	23	24
BA2	Ap	0-6	18.4	1.70	–	–	–	11.4	438	1.30	0.8	9.1	40.2	81	15	127	65	10	10	15
Bowannie	Ap/C	6-16	5.0	0.45	–	–	–	11.0	336	1.43	4.7	9.7	26.5	29	5	74	6	8	14	12
	Btk	16-30	5.5	0.41	–	–	–	13.3	338	1.30	1.9	4.3	17.2	32	5	61	9	12	21	18
	Bt1	30-40	5.9	0.62	–	–	–	11.5	227	1.60	1.8	4.8	17.5	30	5	59	11	12	24	17
	Bt2	40-63	10.3	0.93	–	–	–	11.1	386	1.63	0.5	1.5	6.2	12	5	26	12	27	39	35
	Btk	63-90	8.0	0.72	–	–	–	11.1	342	1.58	0.4	1.8	8.8	20	7	39	12	18	31	30
	Auger	225-240	8.4	0.88	–	–	–	12.4	418	–	0.4	0.8	2.0	5	4	13	14	31	46	43
BA3	Ap	0-14	14.5	0.89	–	–	–	16.4	284	1.46	0.9	1.8	8.4	22	20	53	13	16	28	19
Boyuka	BAt	14-28	14.0	0.94	–	–	–	14.8	282	1.38	0.5	1.0	4.8	13	18	38	11	24	35	30
	Bt1	28-40	13.3	0.90	–	–	–	14.8	278	1.52	0.0	1.0	4.1	10	11	25	14	28	43	32
	BCt2	40-60	12.6	0.77	–	–	–	18.2	292	1.54	0.0	0.8	1.2	8	15	26	13	28	42	33
	BCt	60-81	12.7	0.65	–	–	–	19.5	281	1.28	0.0	0.0	1.7	11	24	37	23	16	38	25
	C	81-90	10.8	0.62	–	–	–	20.7	240	1.38	0.1	1.3	10.1	21	18	52	14	14	28	20
BU1	A	0-5	24.8	1.75	–	–	–	14.2	344	1.28	0.4	1.3	4.7	11	12	31	29	21	50	19
[illegible]	BAt	5-12	12.4	0.80	–	–	–	13.4	366	1.43	0.5	2.3	9.2	23	12	48	20	16	36	16
	Bt1	12-30	10.3	0.87	–	–	–	15.3	241	1.61	0.9	2.1	8.6	27	13	52	13	13	28	22
	Bt2	30-56	6.8	0.47	–	–	–	14.7	222	1.82	1.1	3.3	14.2	29	12	60	14	7	21	19
	2C1	56-80	2.0	0.22	–	–	–	8.7	148	1.51	1.2	8.4	41.1	31	3	85	2	3	5	9
	3C2	80-87	10.8	0.51	–	–	–	21.2	206	1.36	0.5	1.9	36.4	25	13	48	19	14	33	21
	Alluvial pocket	88-100	3.2	0.26	–	–	–	12.1	164	1.61	2.3	6.0	18.1	41	8	77	5	6	11	11
	4C3	87-108	2.4	0.24	–	–	–	10.0	155	1.40	0.6	2.1	13.9	40	11	68	8	8	16	16
	4C4	108-123	4.0	0.31	–	–	–	12.9	188	1.41	0.2	1.3	20.3	53	8	84	4	4	8	9
	4C5	123-130	4.3	0.27	–	–	–	15.7	183	1.47	1.1	6.3	14.3	37	12	71	9	7	15	14
	Auger	236-246	1.8	0.20	–	–	–	8.6	175	–	0.5	17.7	28.8	21	3	81	4	6	9	9
BU2	A	0-14	7.7	0.61	–	–	–	12.7	241	1.80	1.4	5.6	20.5	38	8	74	9	8	17	8
Quandelacy	BAt	14-46	4.2	0.39	–	–	–	10.8	165	1.48	0.7	3.0	21.8	46	8	78	6	5	11	10
	BCt	46-80	6.7	0.39	–	–	–	17.2	188	1.48	0.4	1.6	13.7	40	13	68	12	7	19	12
	2C1	50-60	15.5	0.73	–	–	–	21.1	242	1.38	0.0	0.1	1.9	10	13	25	30	22	52	23
	3C2	60-88	2.2	0.22	–	–	–	10.0	178	1.80	1.7	9.7	38.5	34	3	88	3	4	7	7
	4C3	88-93	2.1	0.24	–	–	–	8.8	181	–	5.6	15.8	38.5	27	3	89	2	3	5	6
	Auger	210-220	9.5	0.85	–	–	–	14.6	330	–	0.2	0.6	3.9	12	6	23	16	26	40	37
BU3	A	0-14	13.9	0.85	–	–	–	16.2	242	1.41	0.9	2.3	10.0	28	16	57	16	12	27	18
Wyaco	Bw	14-34	13.1	0.83	–	–	–	15.7	246	1.25	0.5	2.1	8.4	22	11	45	18	17	36	20
	2C2 (dark band)	43-47	16.5	0.90	–	–	–	17.1	242	1.24	0.2	0.7	3.3	18	21	45	22	16	38	18
	2C2 (light band)	47-51	12.5	0.64	–	–	–	18.4	182	1.31	0.1	1.0	4.0	34	18	63	14	10	24	14
	3Btb	79-92	9.8	0.83	–	–	–	14.5	268	1.20	1.4	2.7	11.7	27	10	54	14	15	29	17
	Auger	165-175	7.0	0.57	–	–	–	12.2	214	–	0.7	1.4	7.6	30	14	54	13	13	28	20

Means and Standard Deviations for Extensive Fields

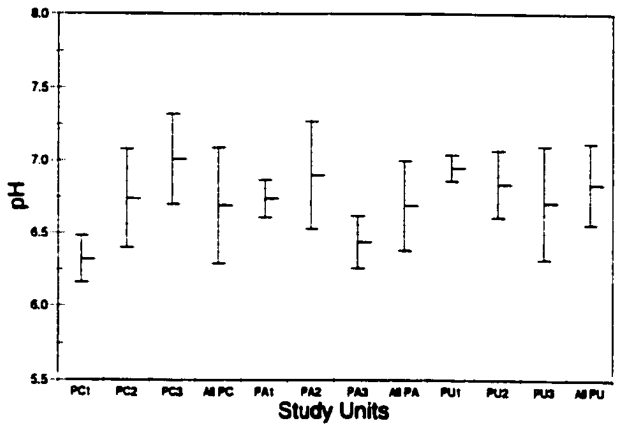
pH: Nutria Study Area



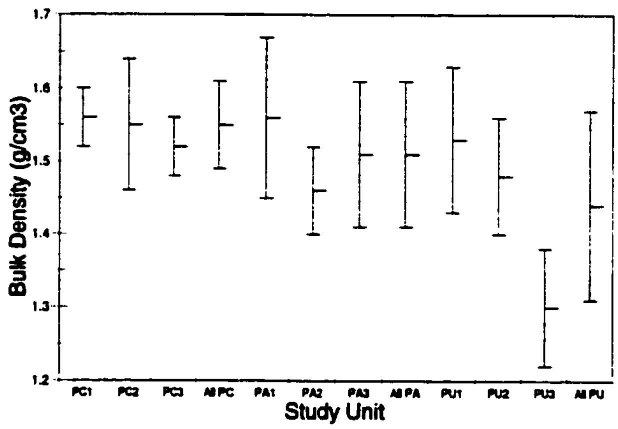
Bulk Density: Nutria Study Area



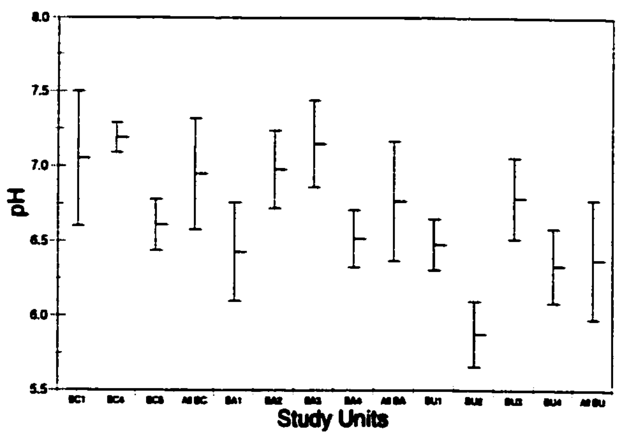
pH: Pescado Study Area



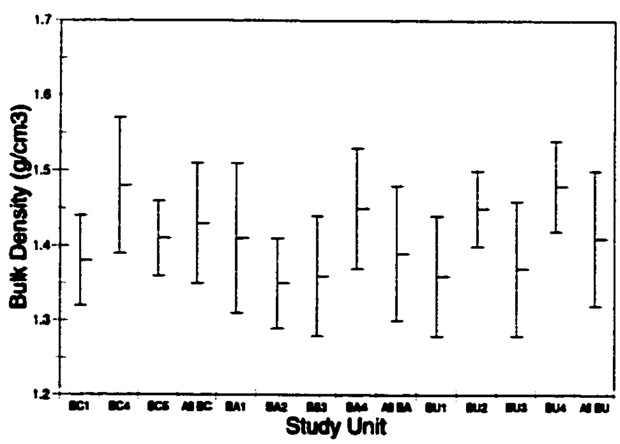
Bulk Density: Pescado Study Area



pH: Bear Canyon Study Area

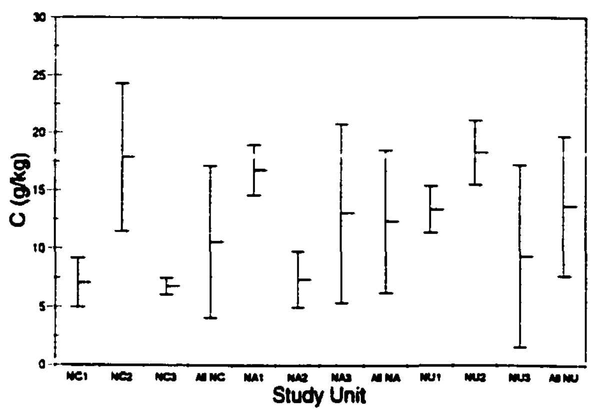


Bulk Density: Bear Canyon Study Area

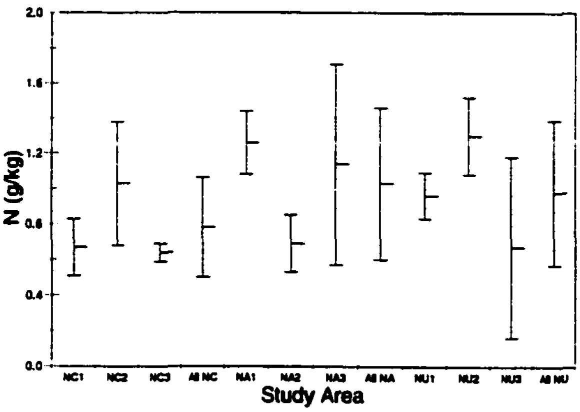


Means and Standard Deviations for Extensive Fields

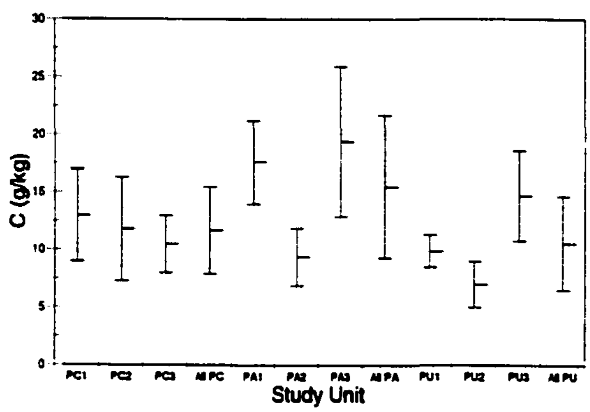
Organic C: Nutria Study Area



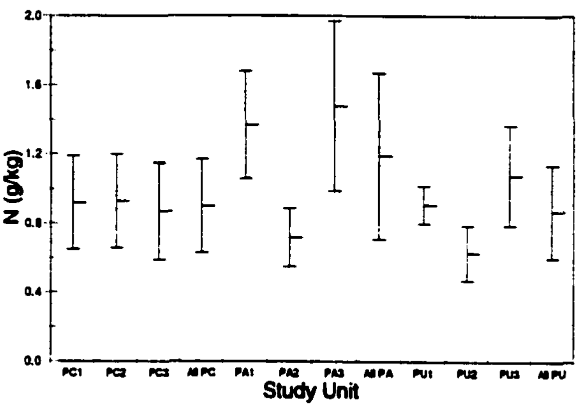
Nitrogen: Nutria Study Area



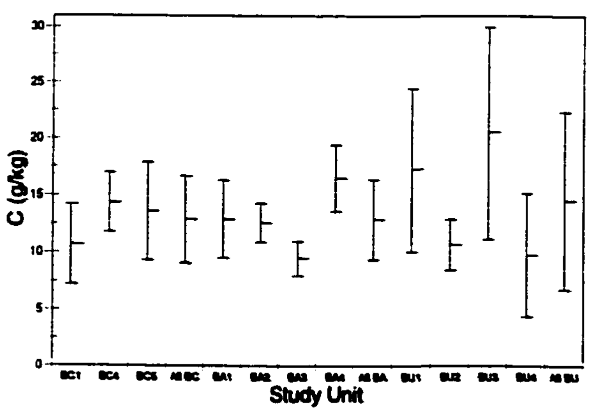
Organic C: Pescado Study Area



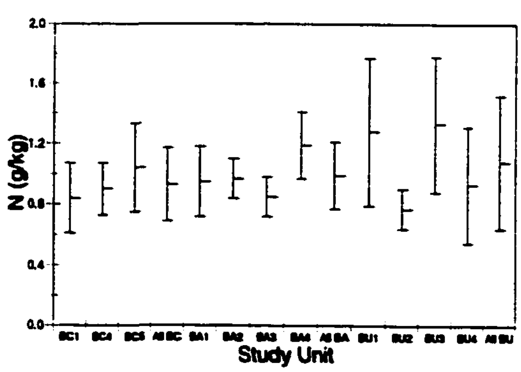
Nitrogen: Pescado Study Area



Organic C: Bear Canyon Study Area

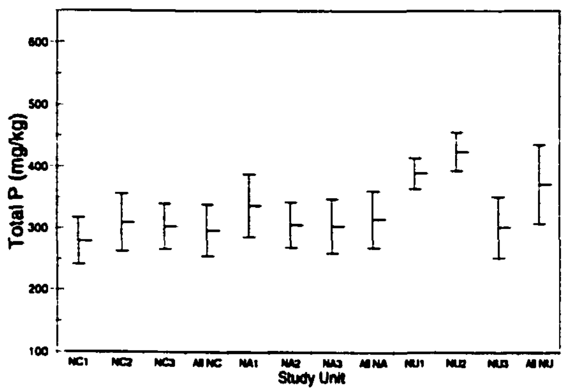


Nitrogen: Bear Canyon Study Area

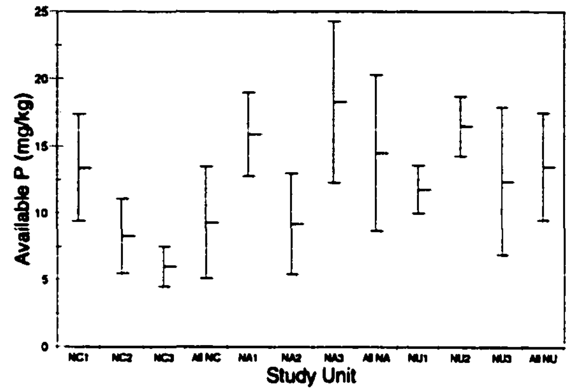


Means and Standard Deviations for Extensive Fields

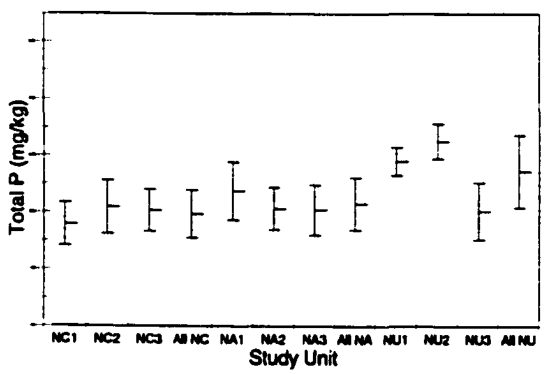
Total P: Nutria Study Area



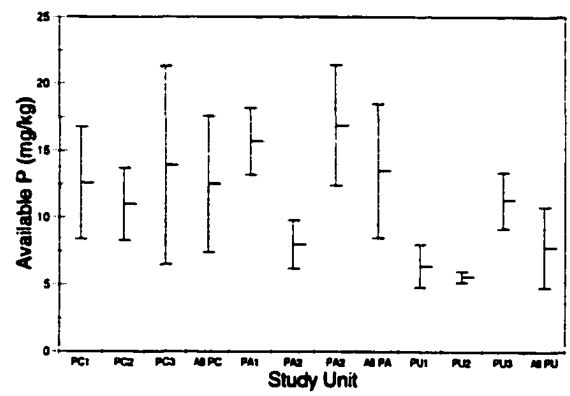
Available P: Nutria Study Area



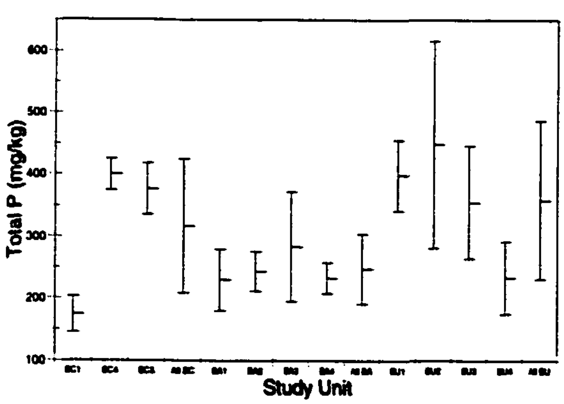
Total P: Nutria Study Area



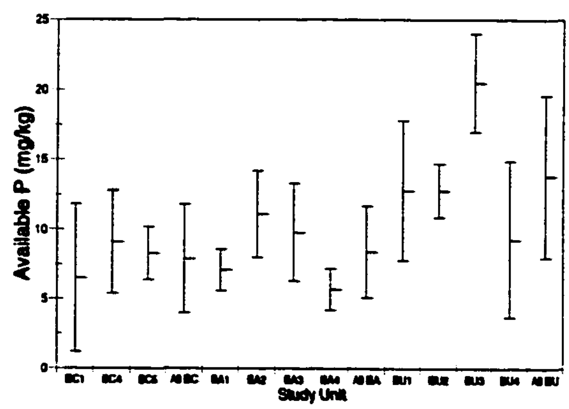
Available P: Pescado Study Area



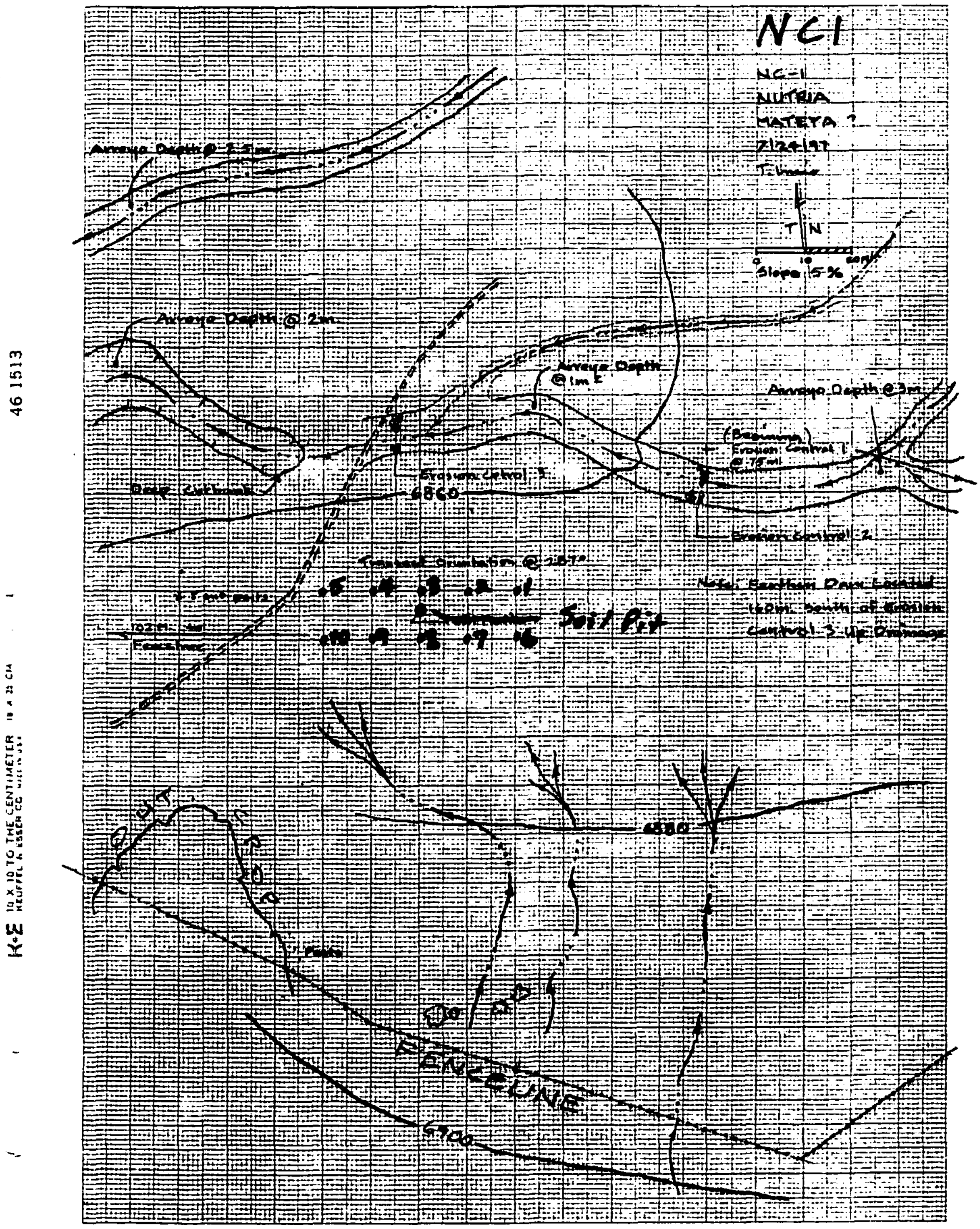
Total P: Bear Canyon Study Area

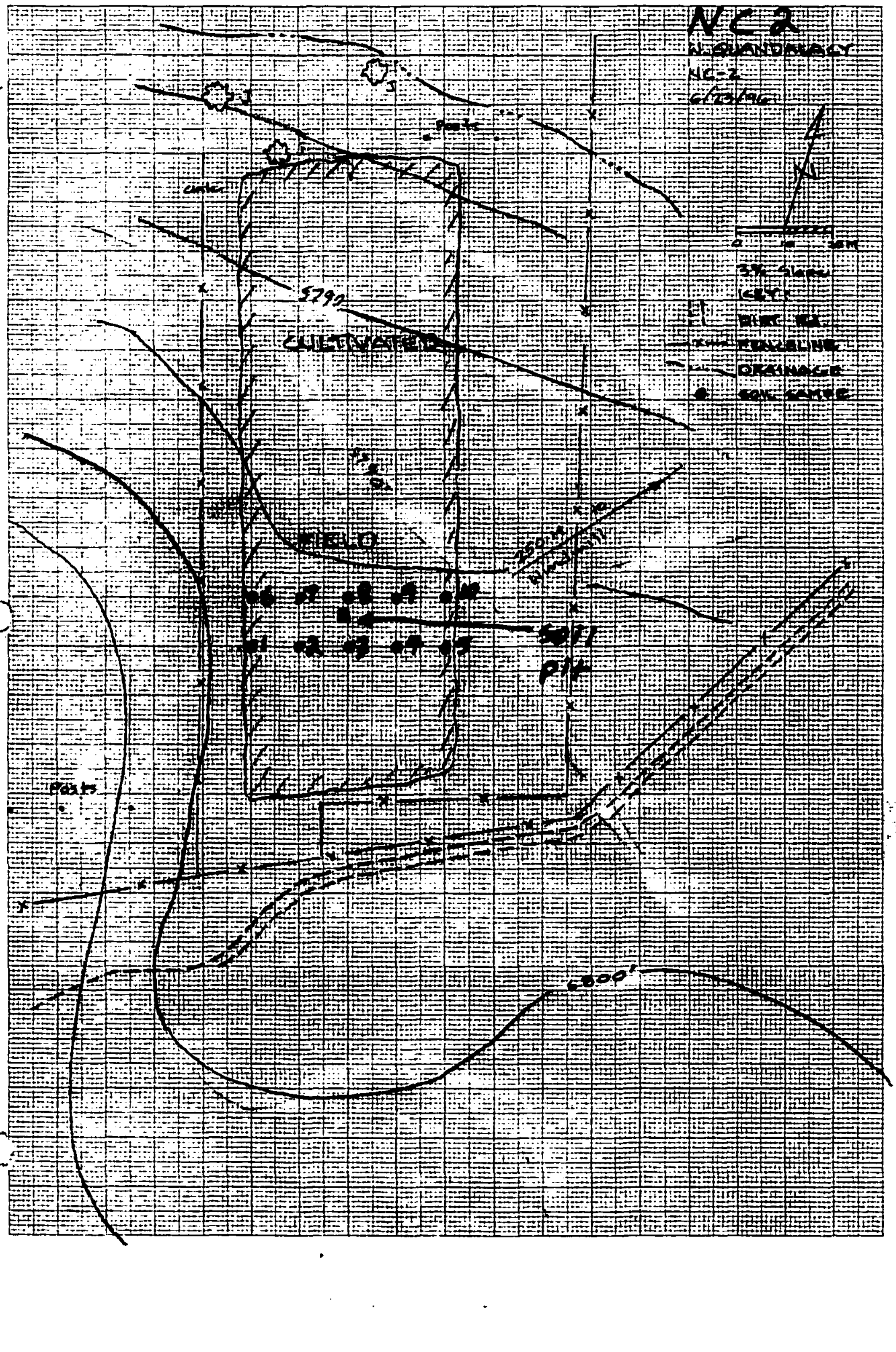


Available P: Bear Canyon Study Area

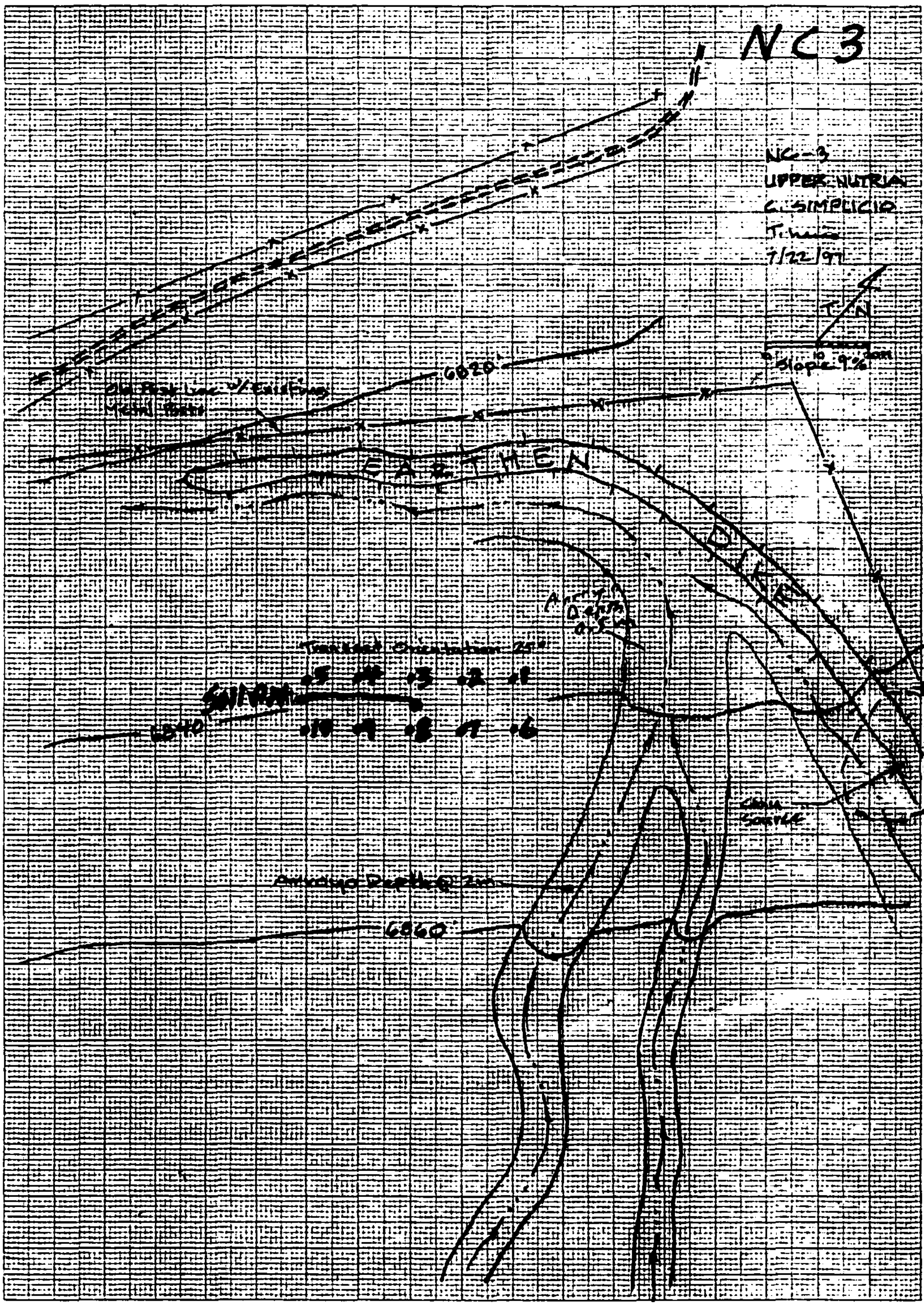


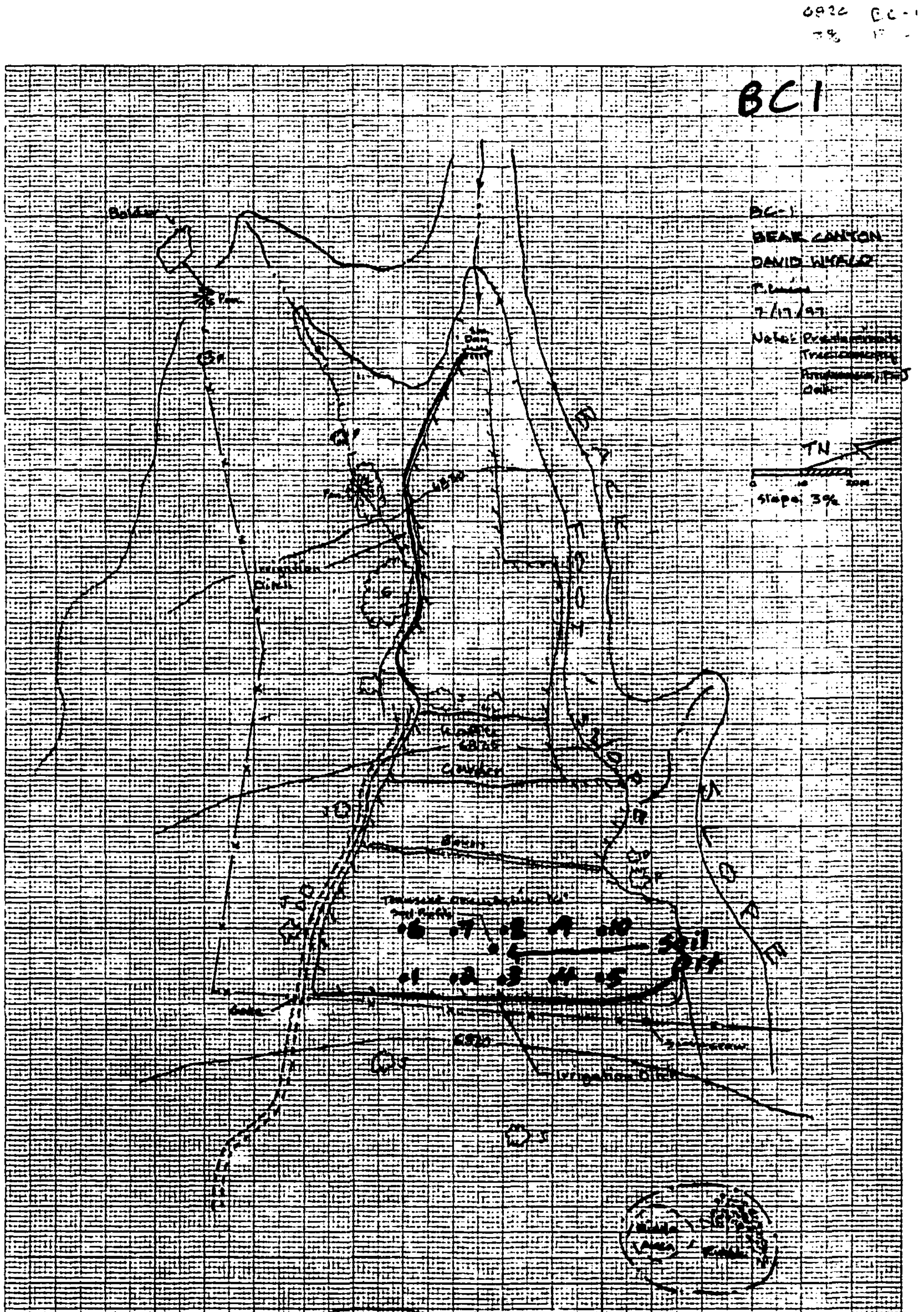
APPENDIX C. SKETCH MAPS OF UNPAIRED ZUNI FIELDS



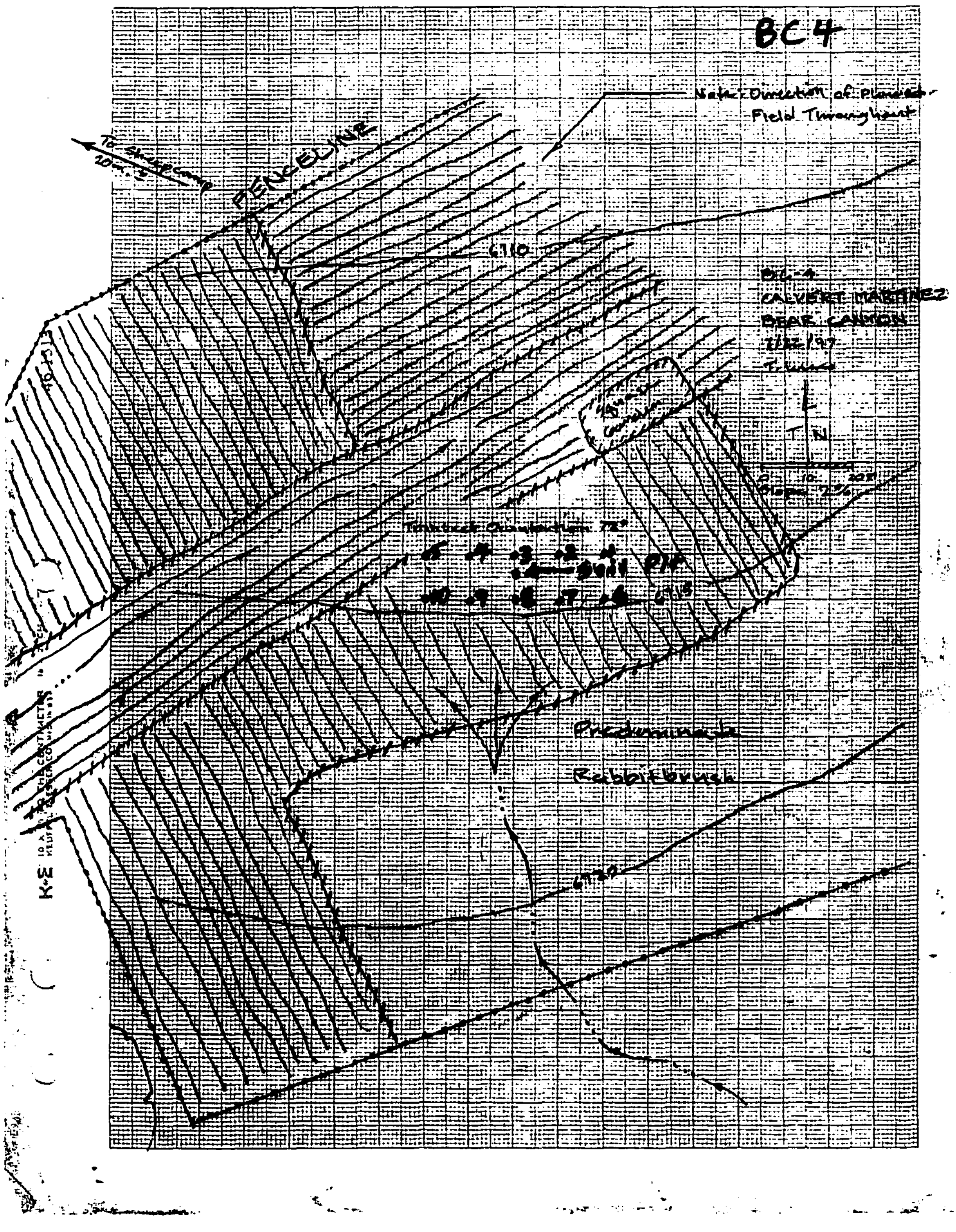


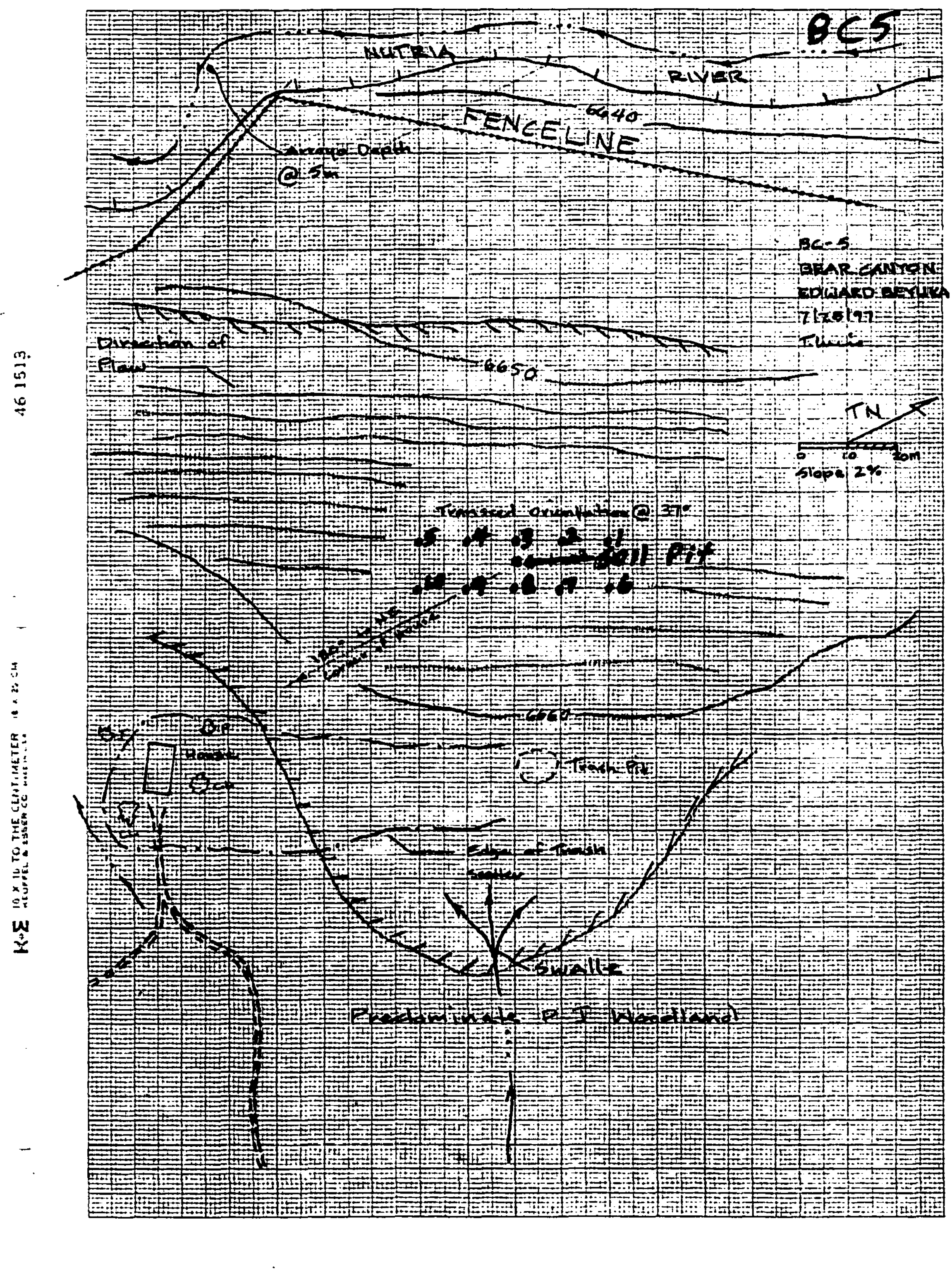
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1513

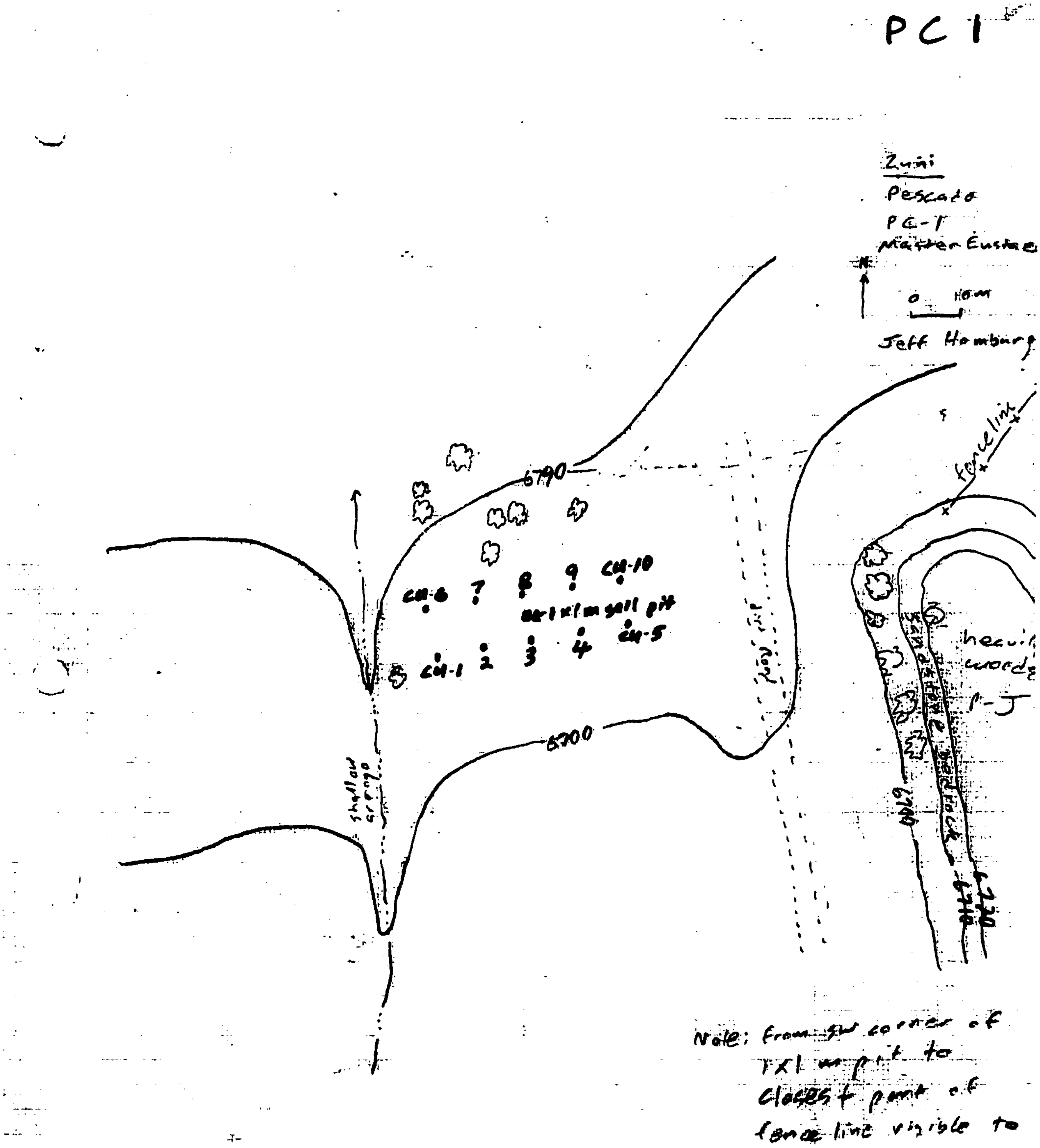

NC3
NC-3
UPPER NUTRIA
C. SIMPLICIO
7/22/97
T N
0 10 20m
Slope 9%
6820
EARTHEN
DIKE
Transect Orientation 25°
5 4 3 2 1
10 9 8 7 6
6840
6860



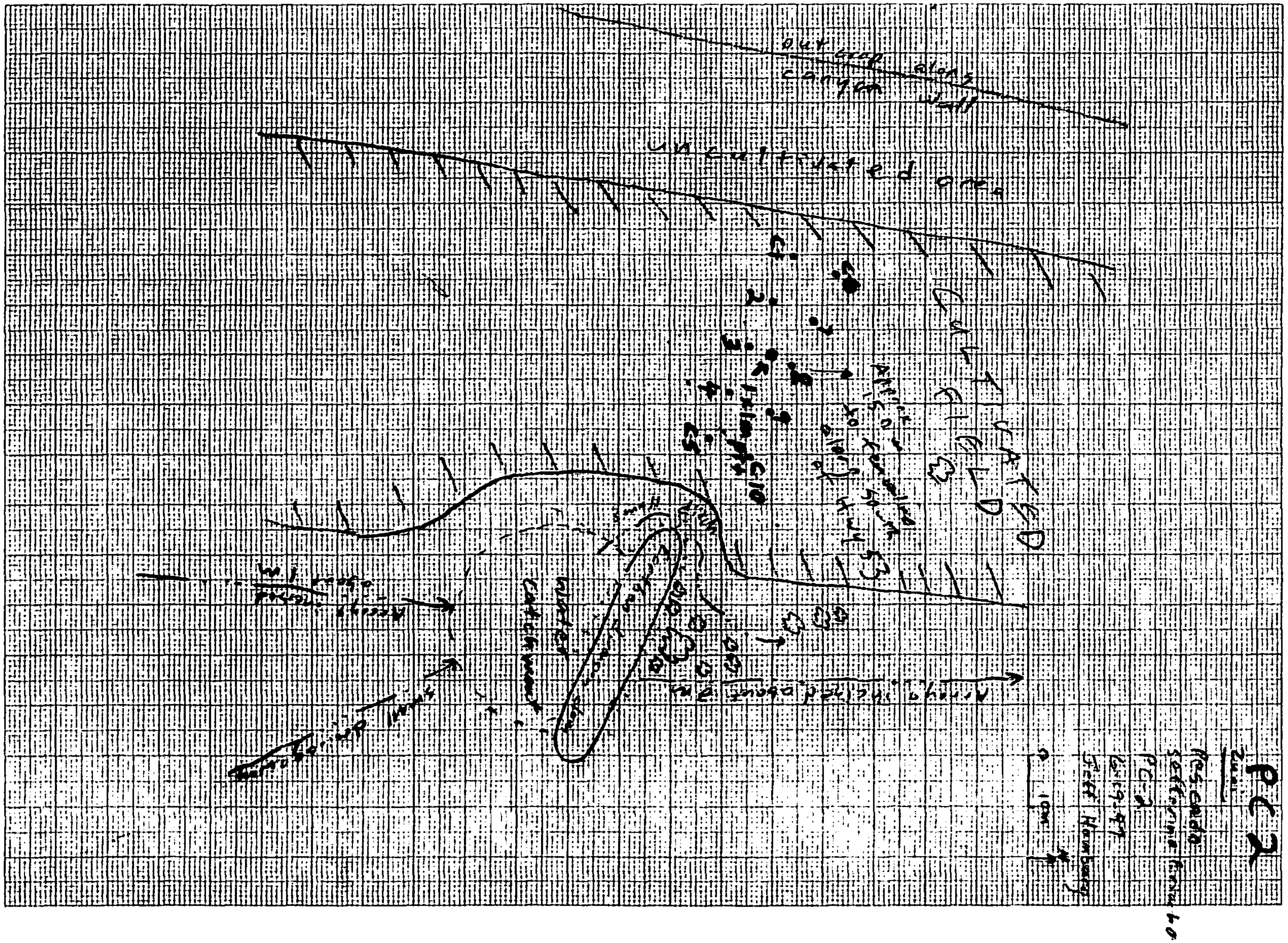
K·E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN USA 46 1513

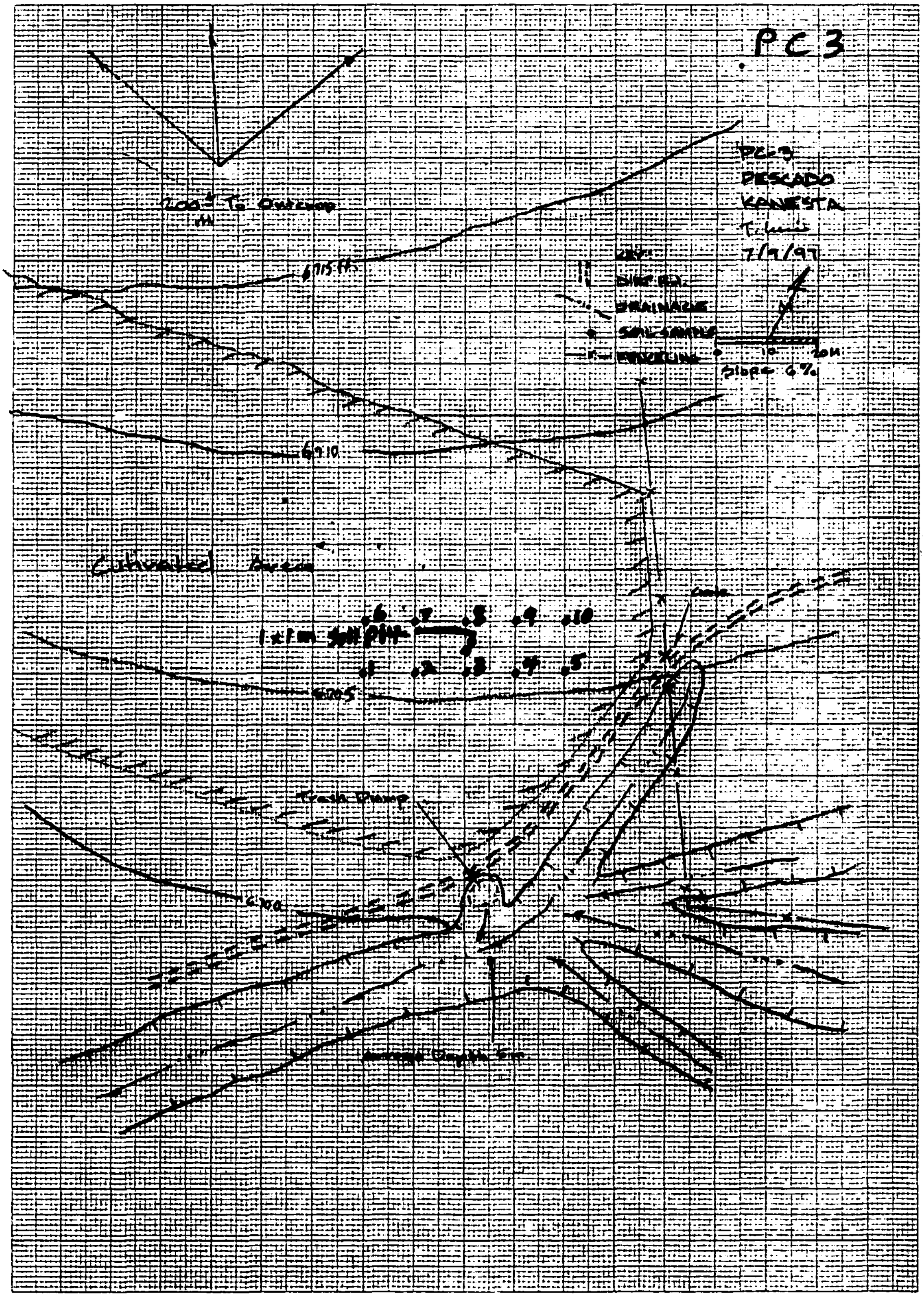

BC4
Note: Direction of Planted Field Throughout
FENCELINE
6710
BC-4
CALVERT MARTINEZ
BEAR CANYON
N
0 10 20
Slope 2%
6715
Predominate
Rabbitbrush
6720

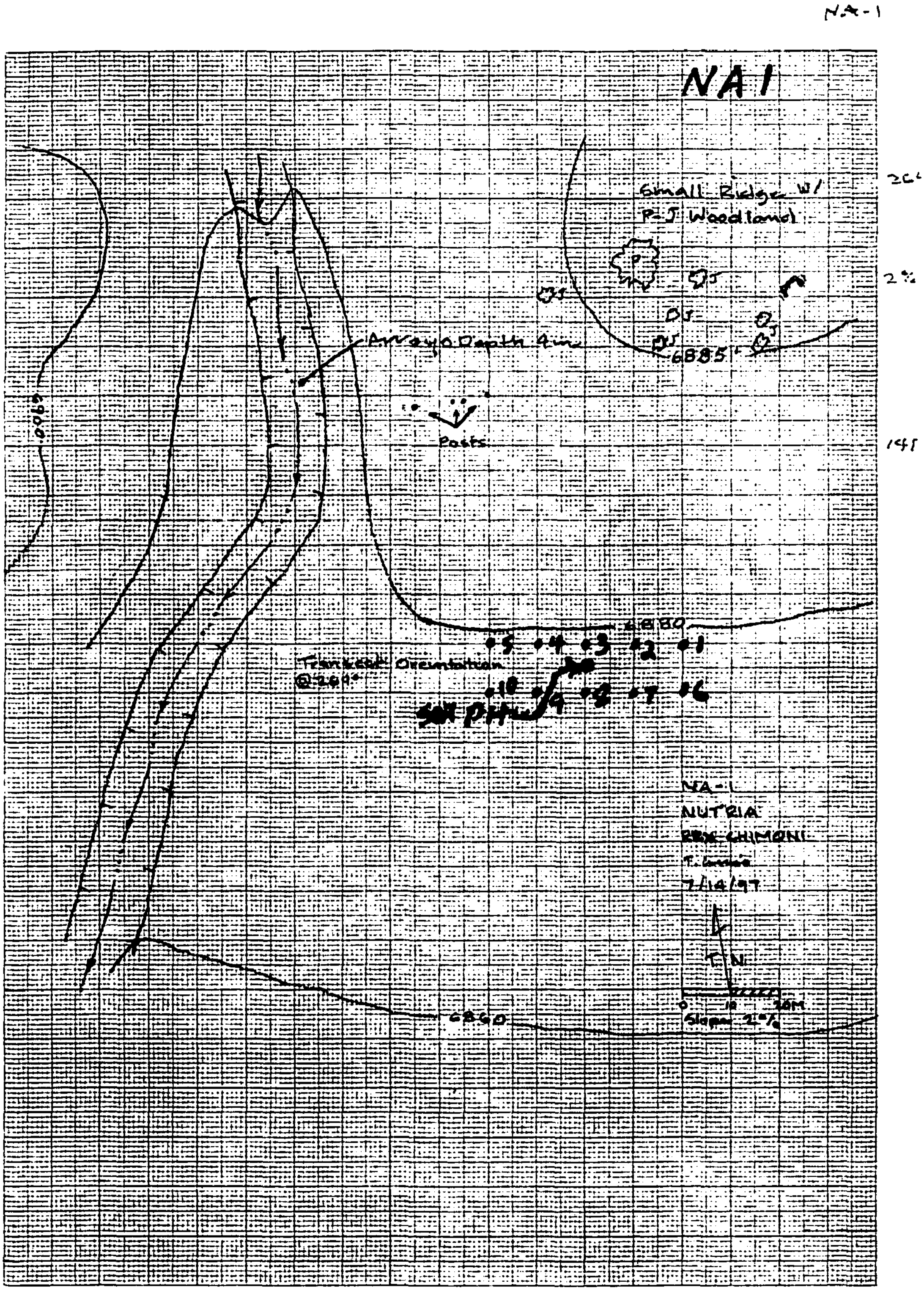

BC5
NUTRIA
RIVER
6640
FENCELINE
Arroyo Depth
@ .5m
BC-5
BEAR CANYON
EDWARD BEYUKA
7/28/97
Direction of
Flow
6650
TN
0 10 20m
Slope 2%
Transect orientation @ 37°
.5 .4 .3 .2 .1
Soil Pit
.10 .9 .8 .7 .6
6660
Trash Pit
House
Edge of Trash
Swale
Predominate P-J Woodland
K+E 10 X 10 TO THE CENTIMETER
46 1513


PC 1
Zuni
Pescado
PC-1
Matter Eustace
N
0 10m
Jeff Hamburg
fence line
6790
6700
shallow arroyo
road
heavily wooded
P-J
sandstone bedrock
6790
6780
6770
CH-6
7
8
9
CH-10
1x1m test pit
CH-1
2
3
4
CH-5
Note: from sw corner of
1x1 m pit to
closest point of
fence line visible to
the east is
10.4 m, at a
bearing of 93°

K·E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1513




PC3
PC3
PESCADO
KANESTA
7/9/97
KEY:
DIRT RD.
DRAINAGE
SOIL SAMPLE
FENCELINE
10
20M
Slope 6%
200± To Outcrop
6715 ft.
6910
Cultivated Area
1×1m Soil Pits
6
7
8
9
10
1
2
3
4
5
6905
Trash Dump
6900



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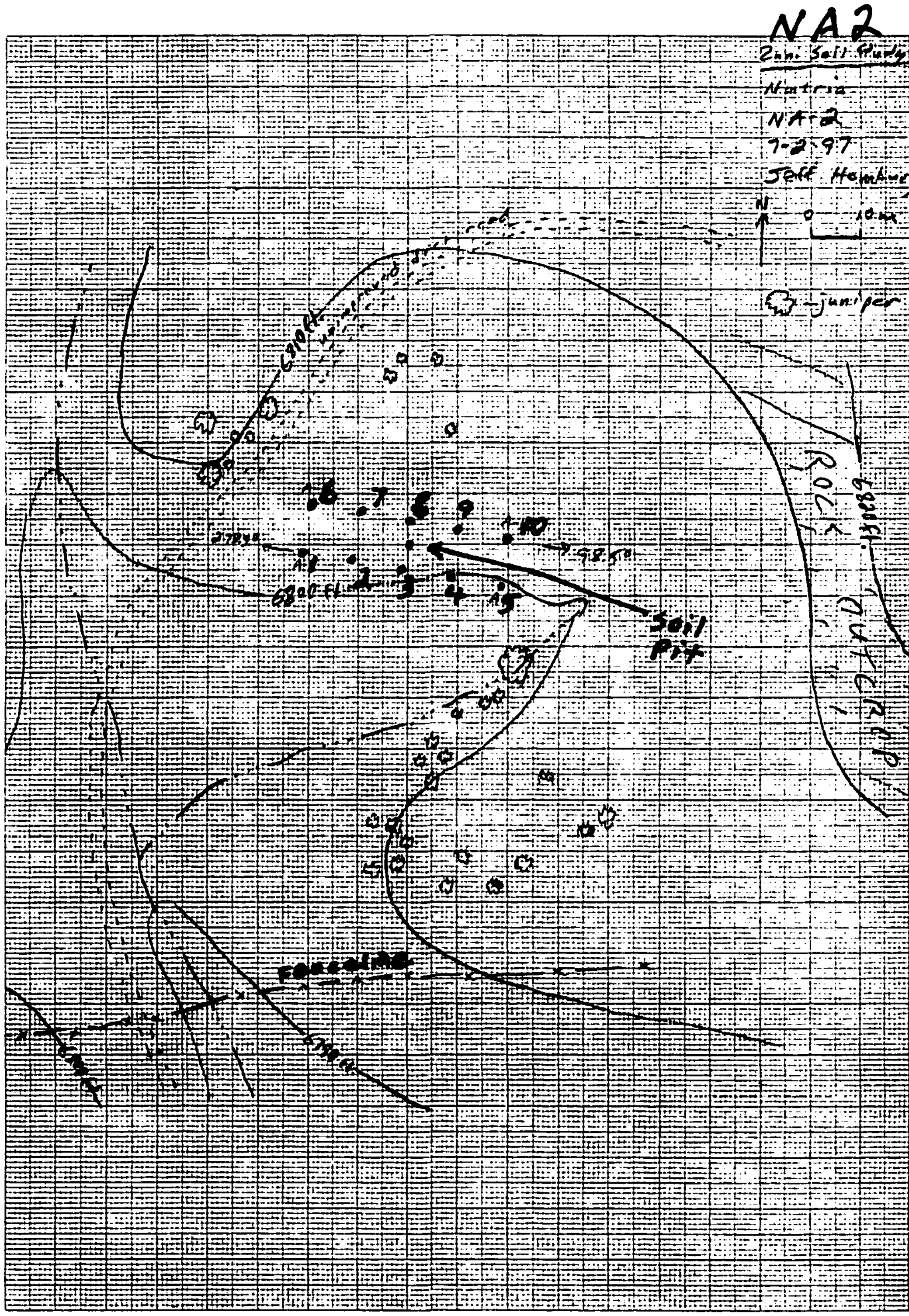
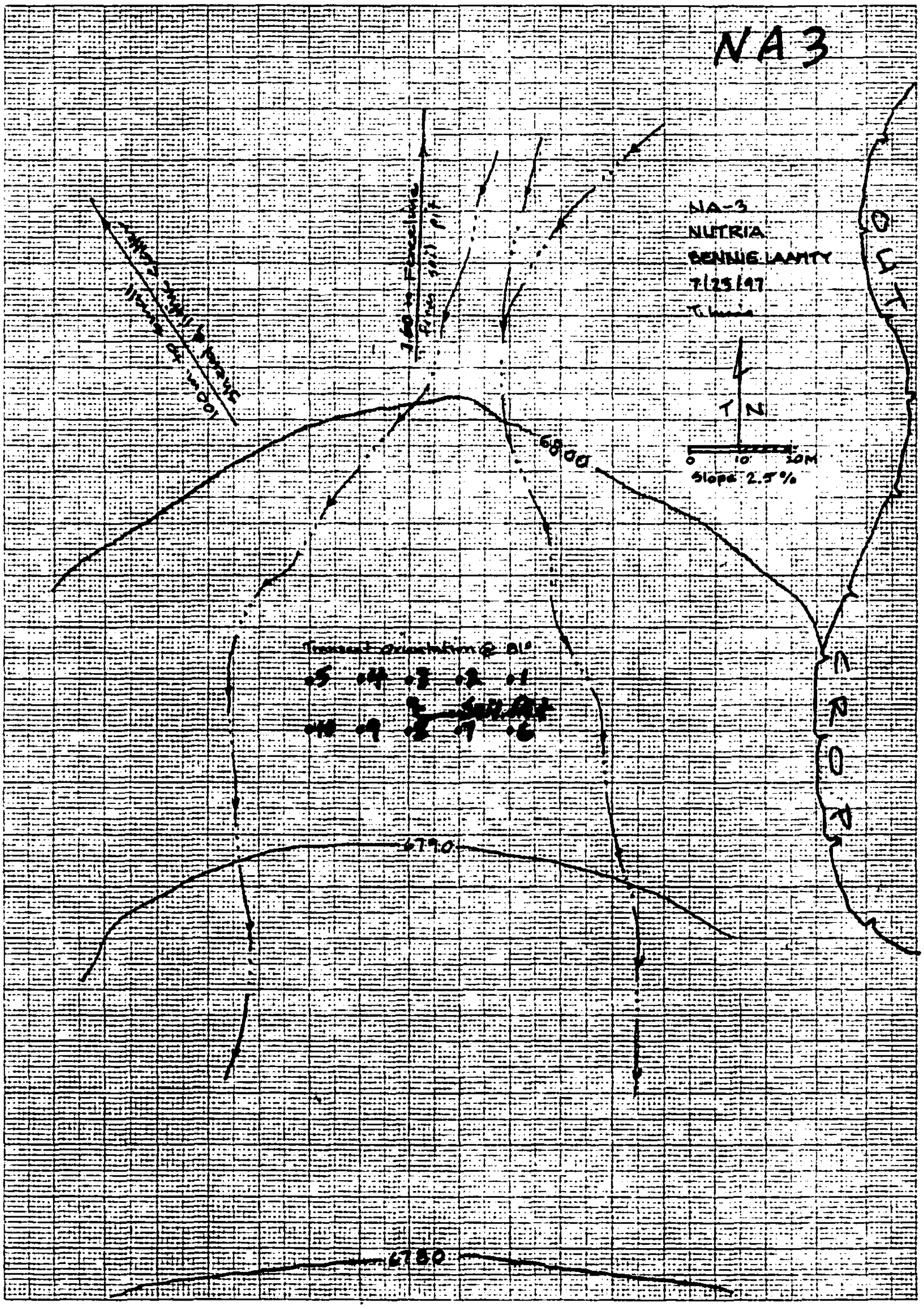
K+E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.



K+E 10 X 10 TO THE CENTIMETER KEUFFEL & ESSER CO.

6790
2.5%



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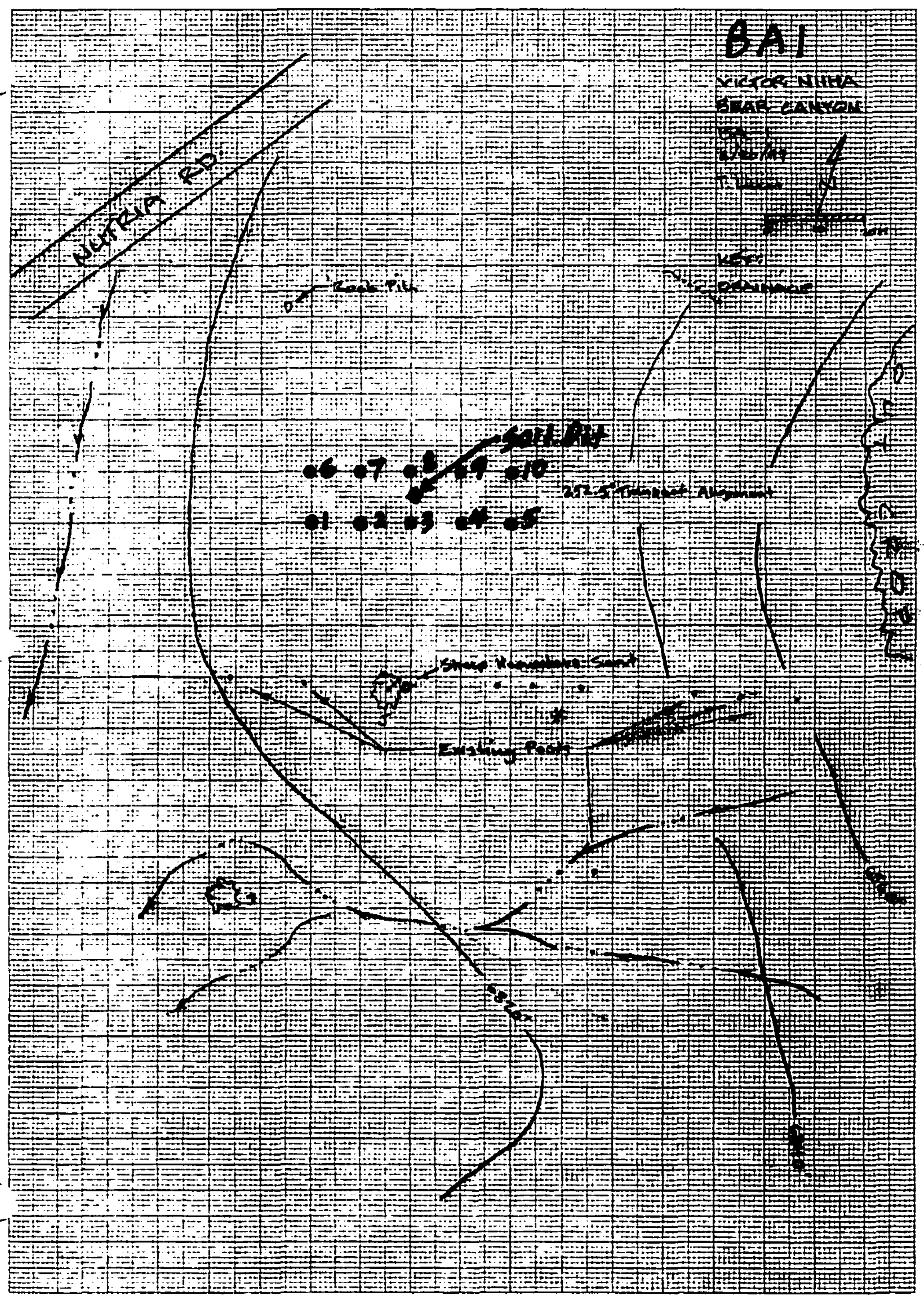
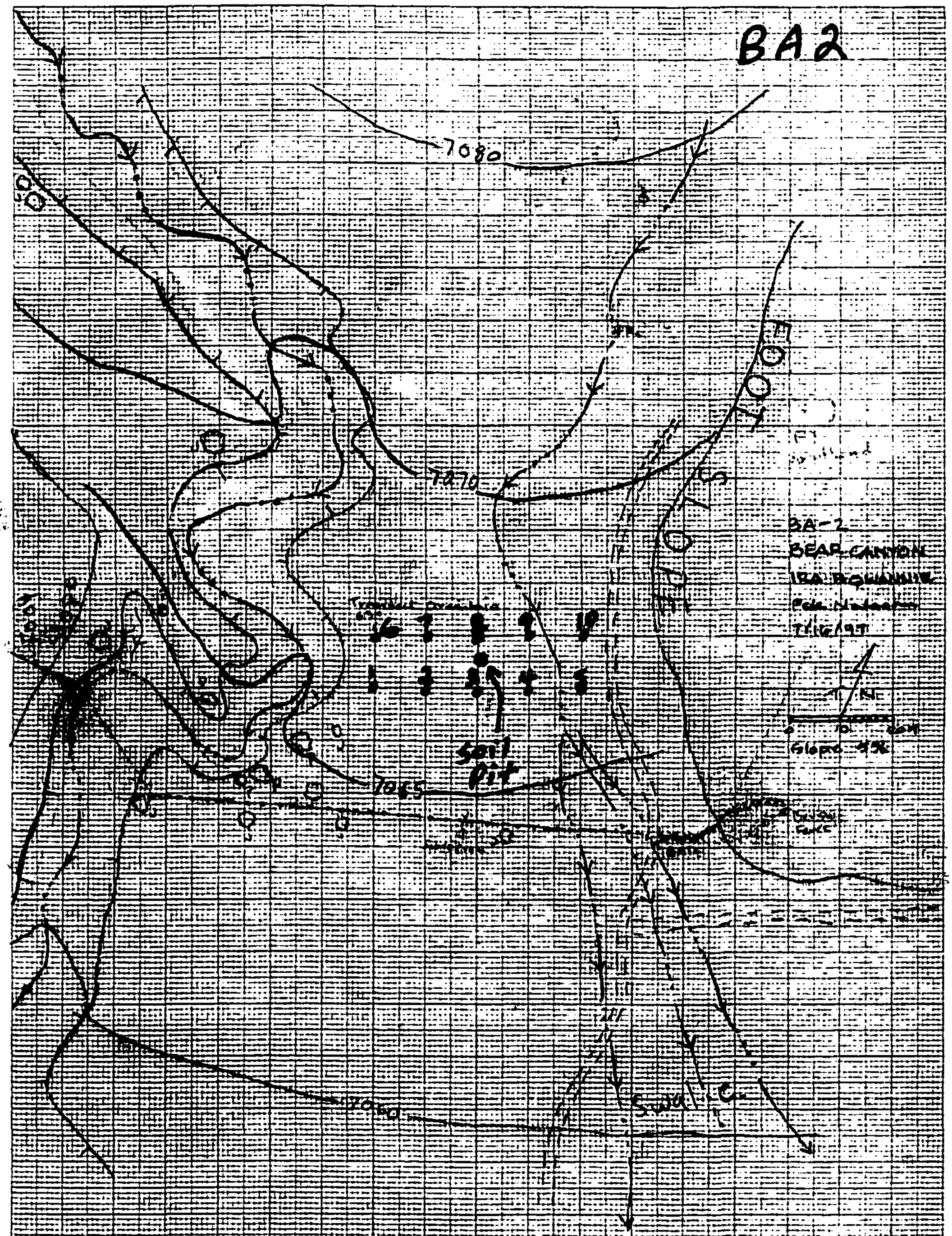
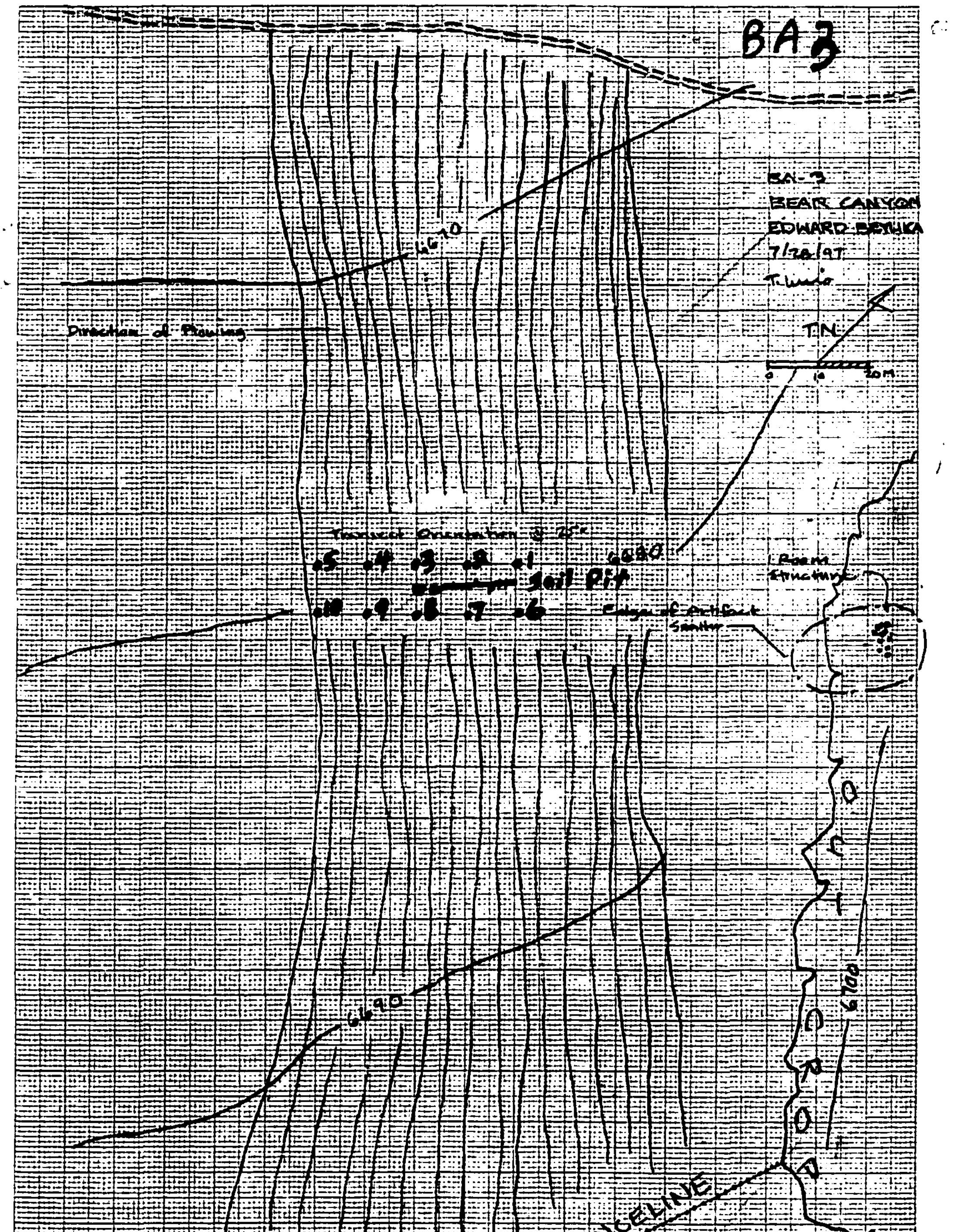
K-E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.



4% slope

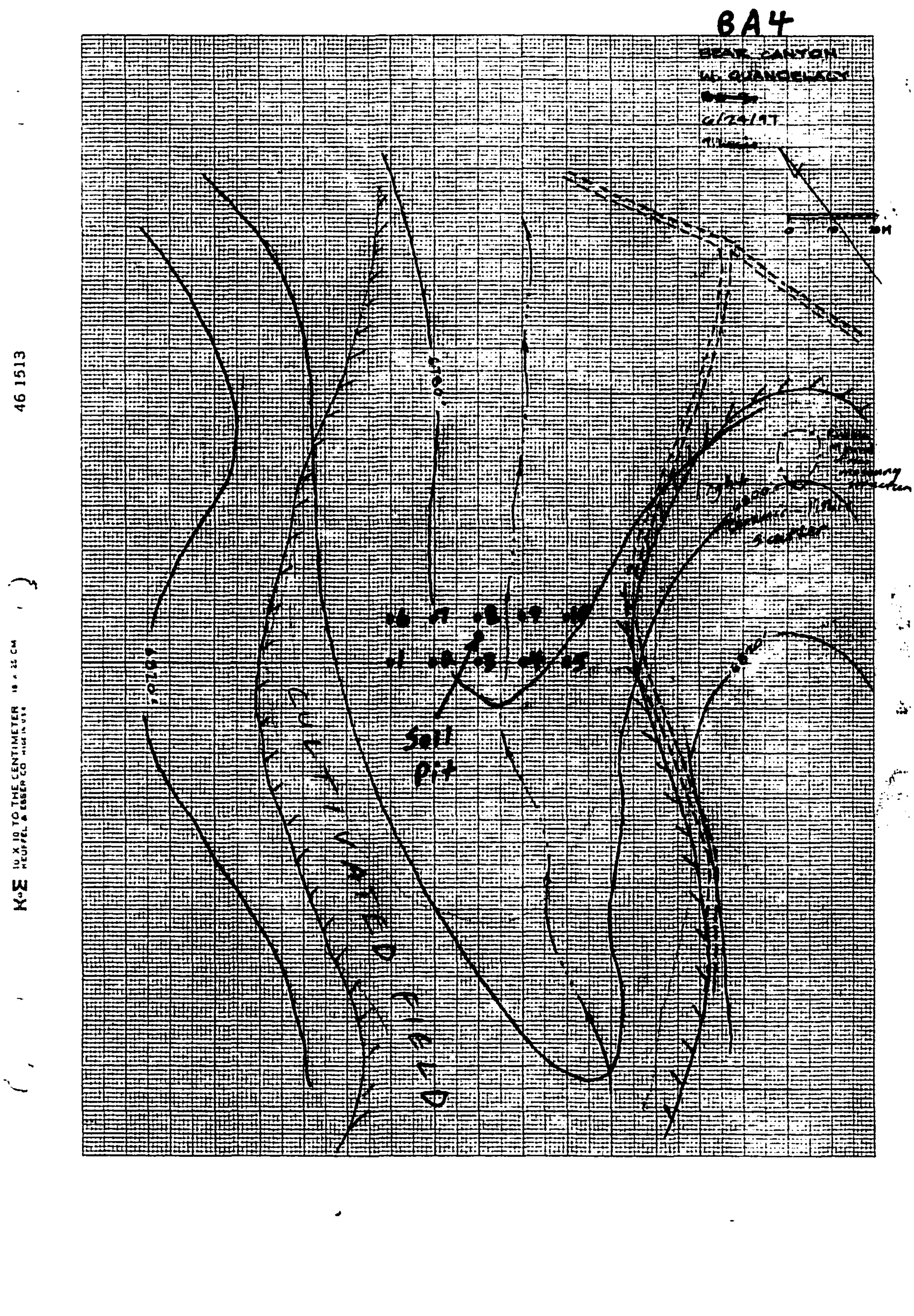
K+E 10 X 10 TO THE CENTIMETER
46 1513


BA2
7080
7070
7065
7060
Soil Pit
BA-2
BEAR CANYON



K•E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO. MADE IN U.S.A.

46 1513


BA4
BEAR CANYON
W. QUANDELACY
6/24/97
0
10
20M
Soil
Pit
CULTIVATED FIELD
K+E 10 X 10 TO THE CENTIMETER 18 x 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.
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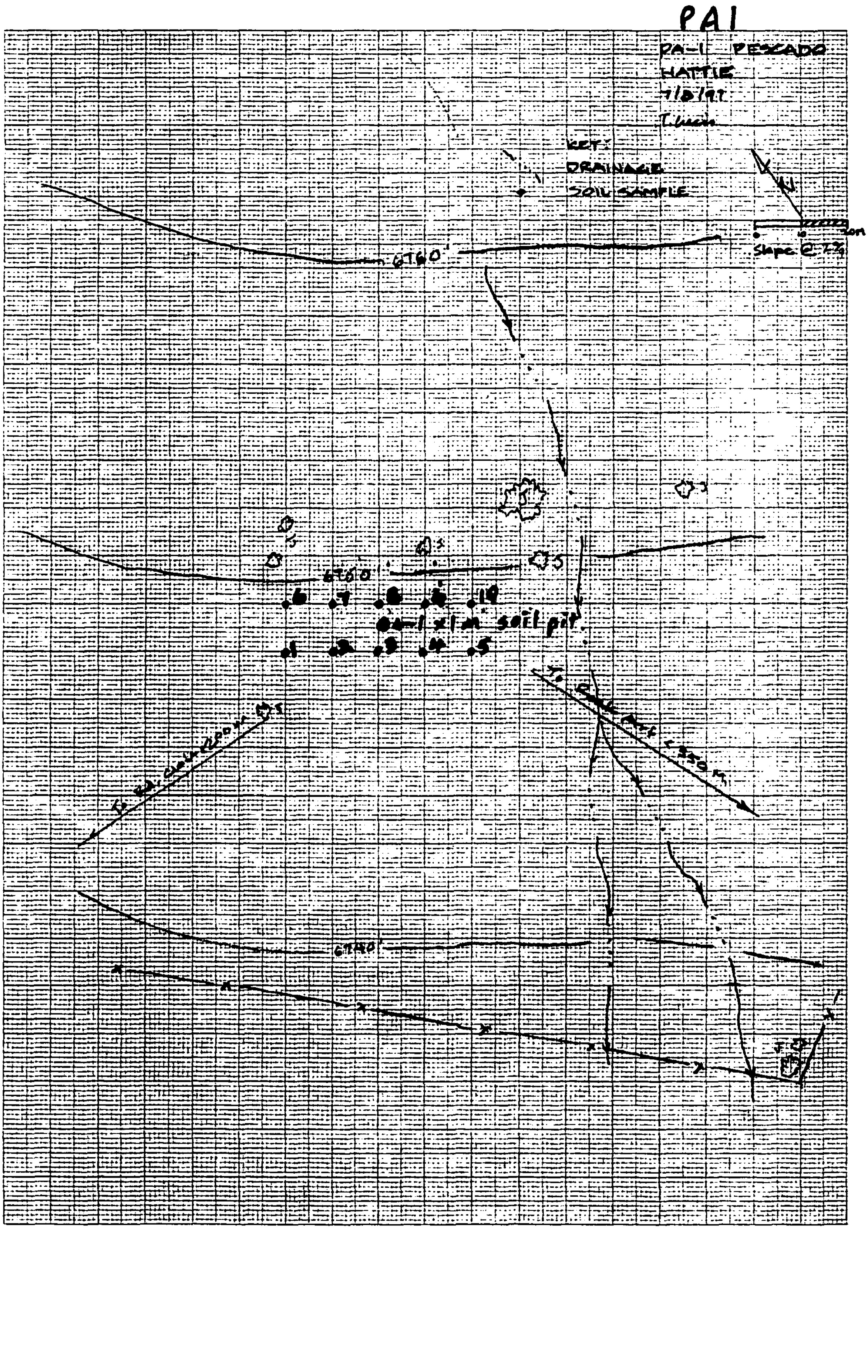
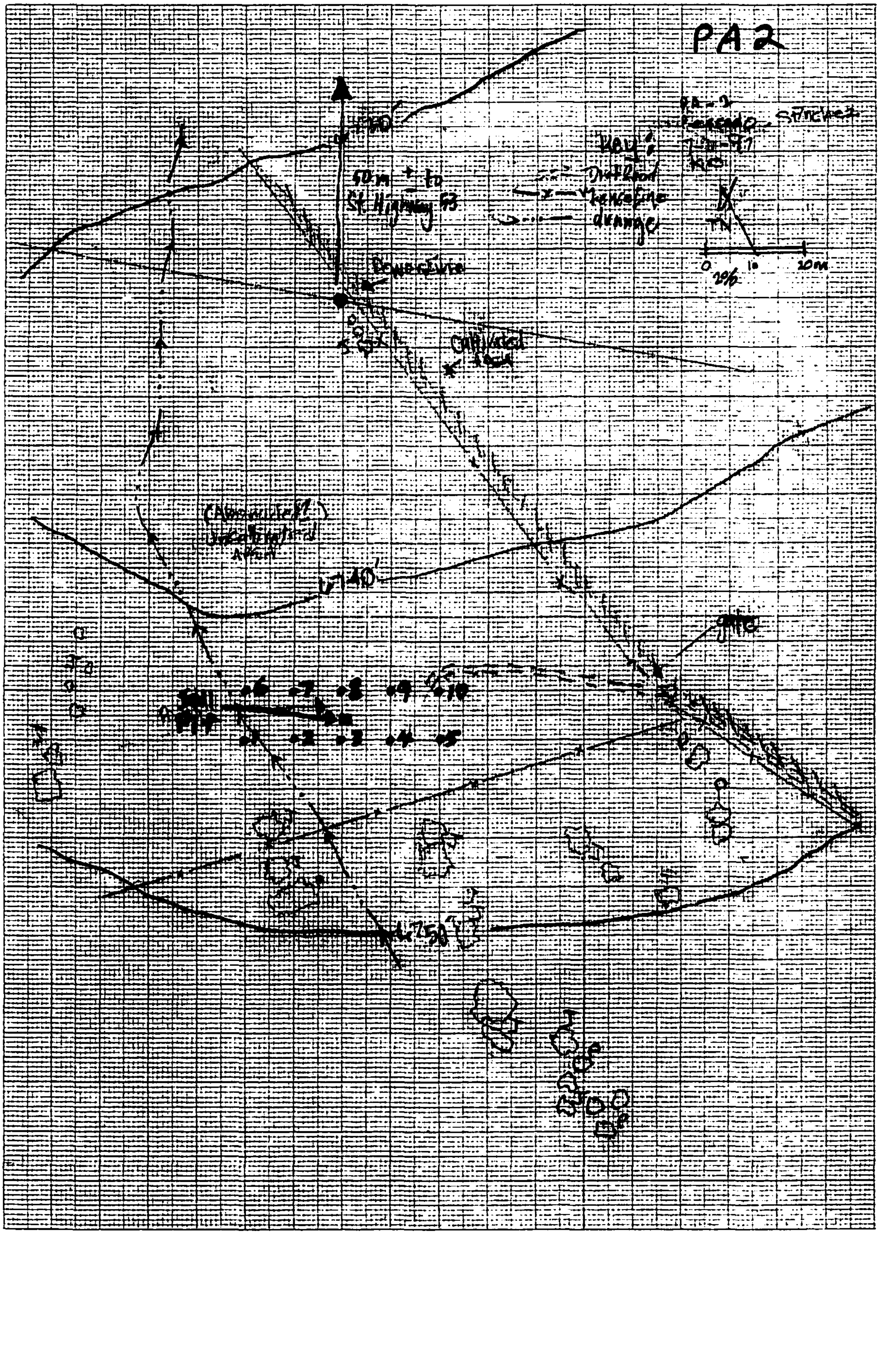
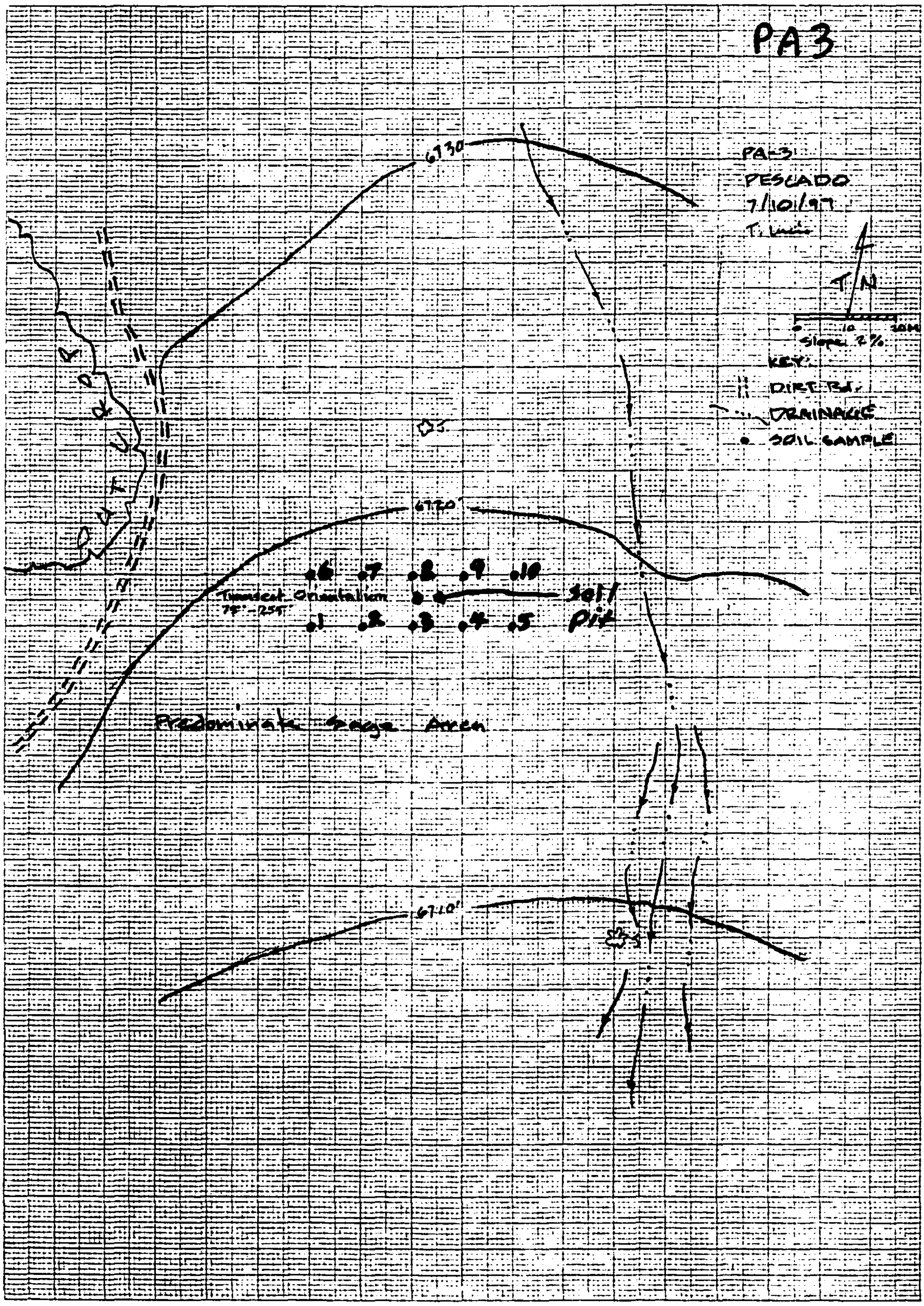
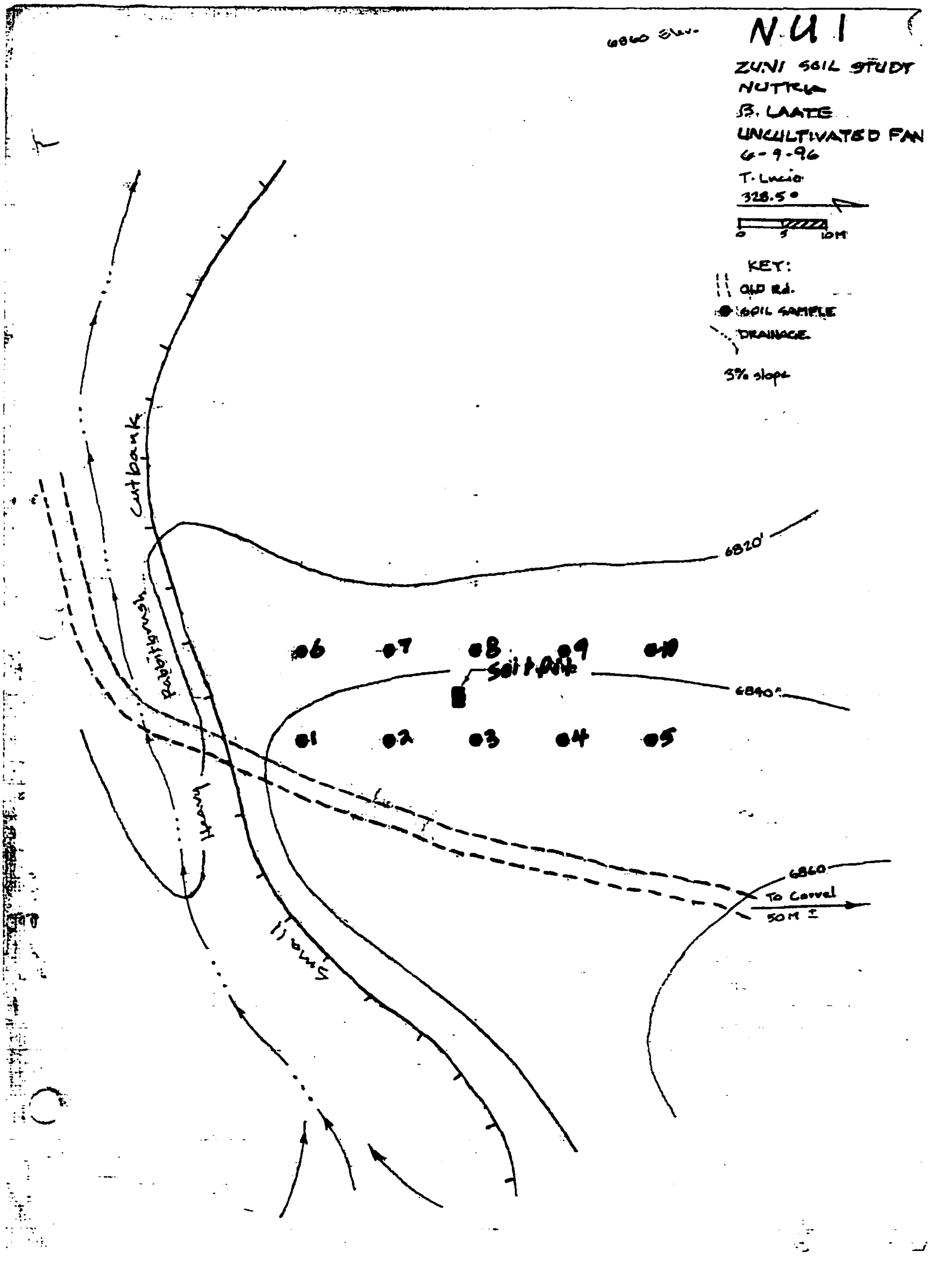
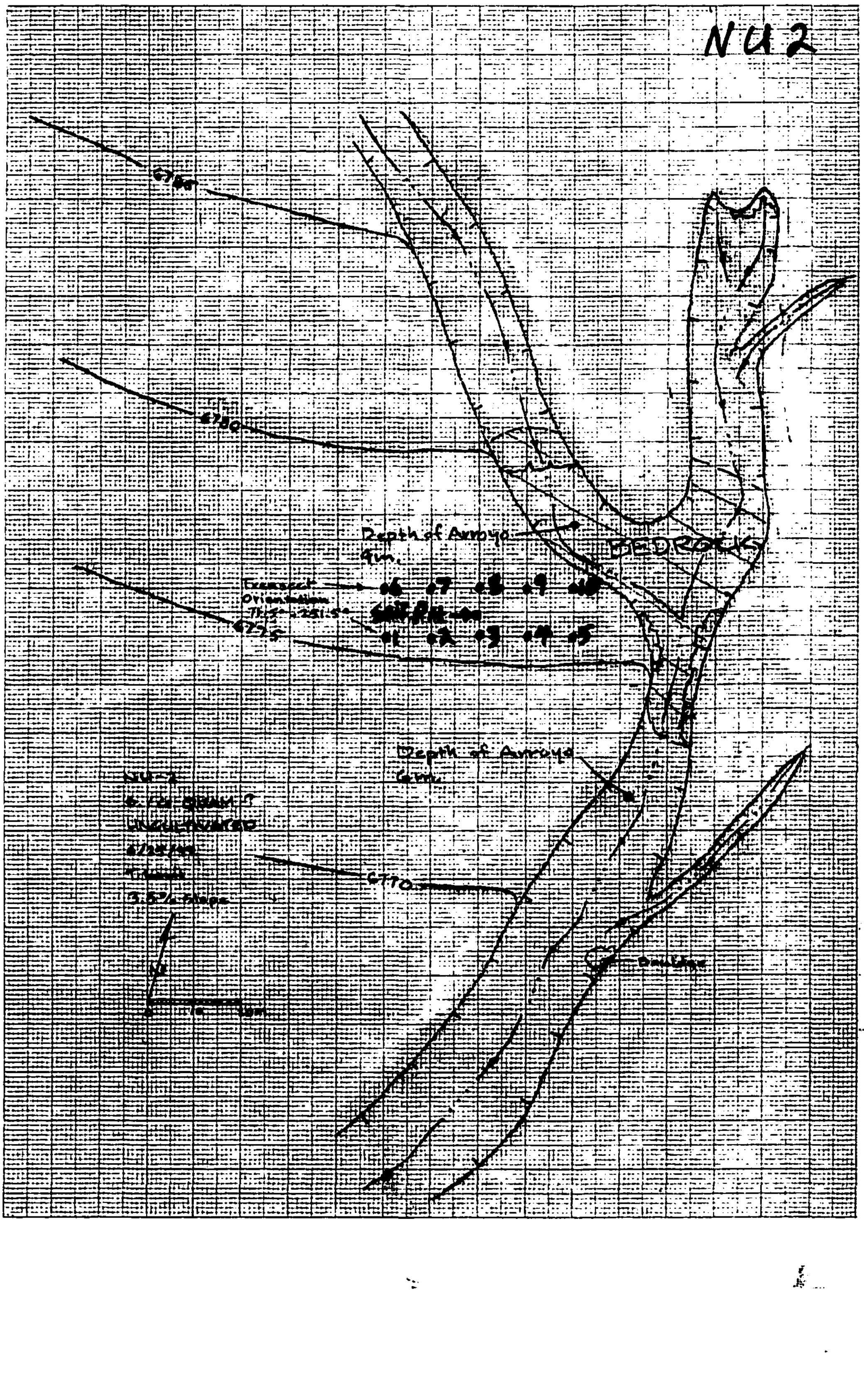

PA1
PA-1 PESCADO
HATTIE
7/8/97
KEY:
DRAINAGE
SOIL SAMPLE
N
0 10 20m
Slope @ 7%
6760'
6760'
6740'
1 x 1 m soil pit
To Cave Art c 350 m
To Rd.


PA2
Key:
Dirt Road
Fenceline
drainage
50m to St. Highway 53
TN
0
10
20M
gate


PA3
6730
PA-3
PESCADO
7/10/97
T N
0 10 20M
Slope 2%
KEY:
DIRT Rd.
DRAINAGE
SOIL SAMPLE
6720'
6
7
8
9
10
Transect Orientation
75°-255°
Soil Pit
1
2
3
4
5
Predominate Sage Area
6710'


6860 Elev.
NU1
ZUNI SOIL STUDY
NUTRIA
B. LAATE
UNCULTIVATED FAN
6-9-96
T. Lucio
328.5°
0 5 10M
KEY:
OLD Rd.
SOIL SAMPLE
DRAINAGE
3% slope
Cutbank
Rabbitbrush
Sand
6820'
6840'
6860
6
7
8
9
10
1
2
3
4
5
To Corral
50M ±



K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.
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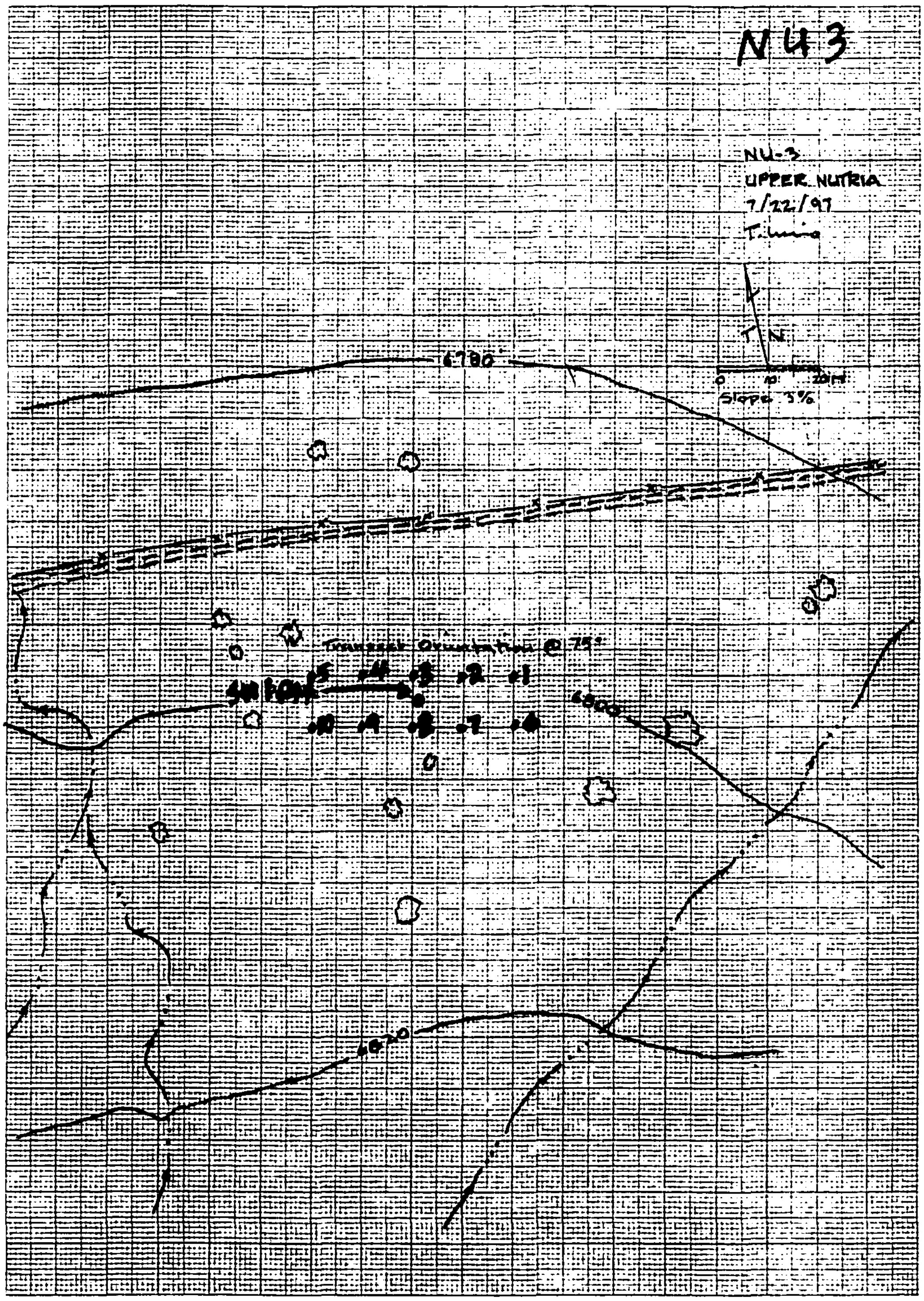
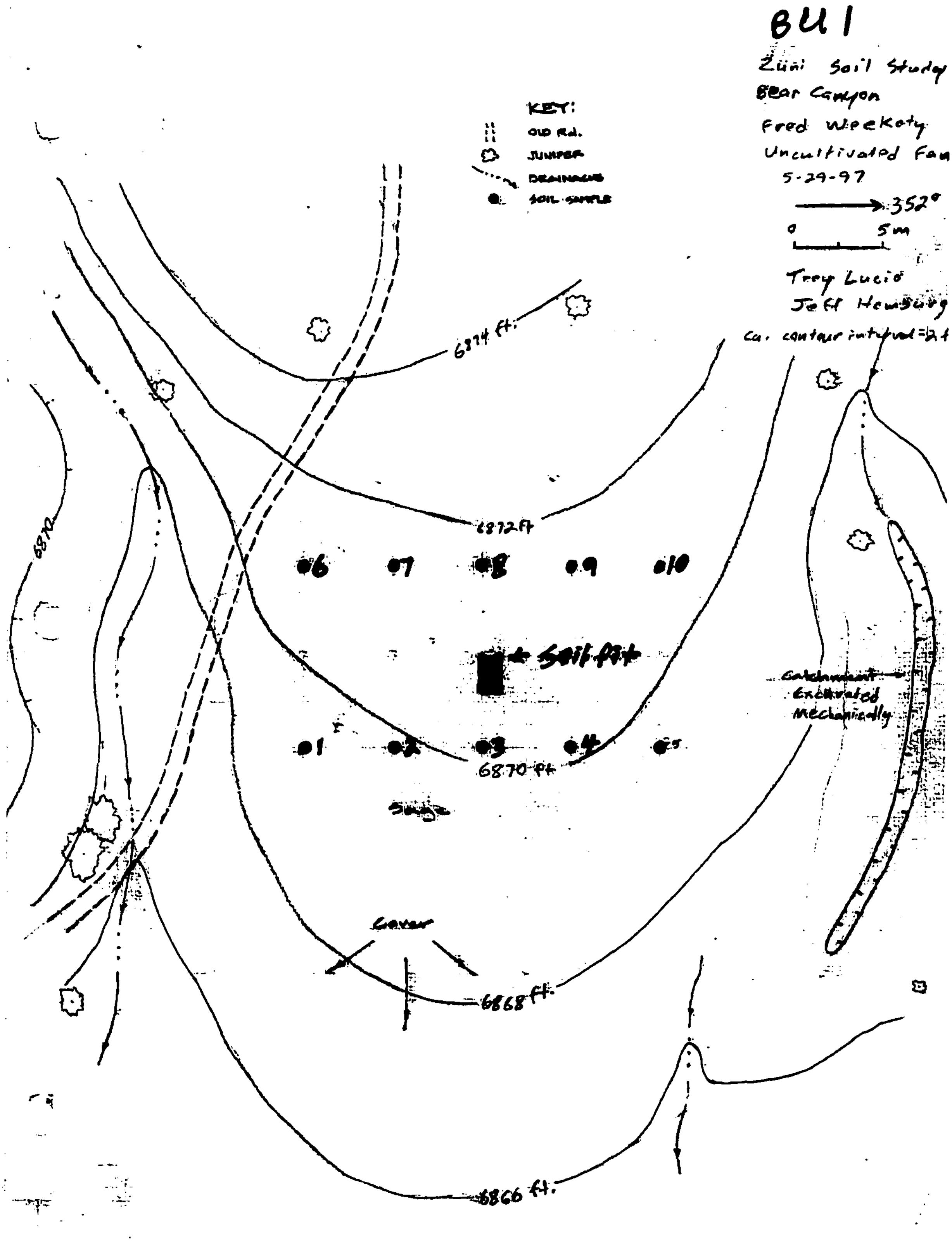
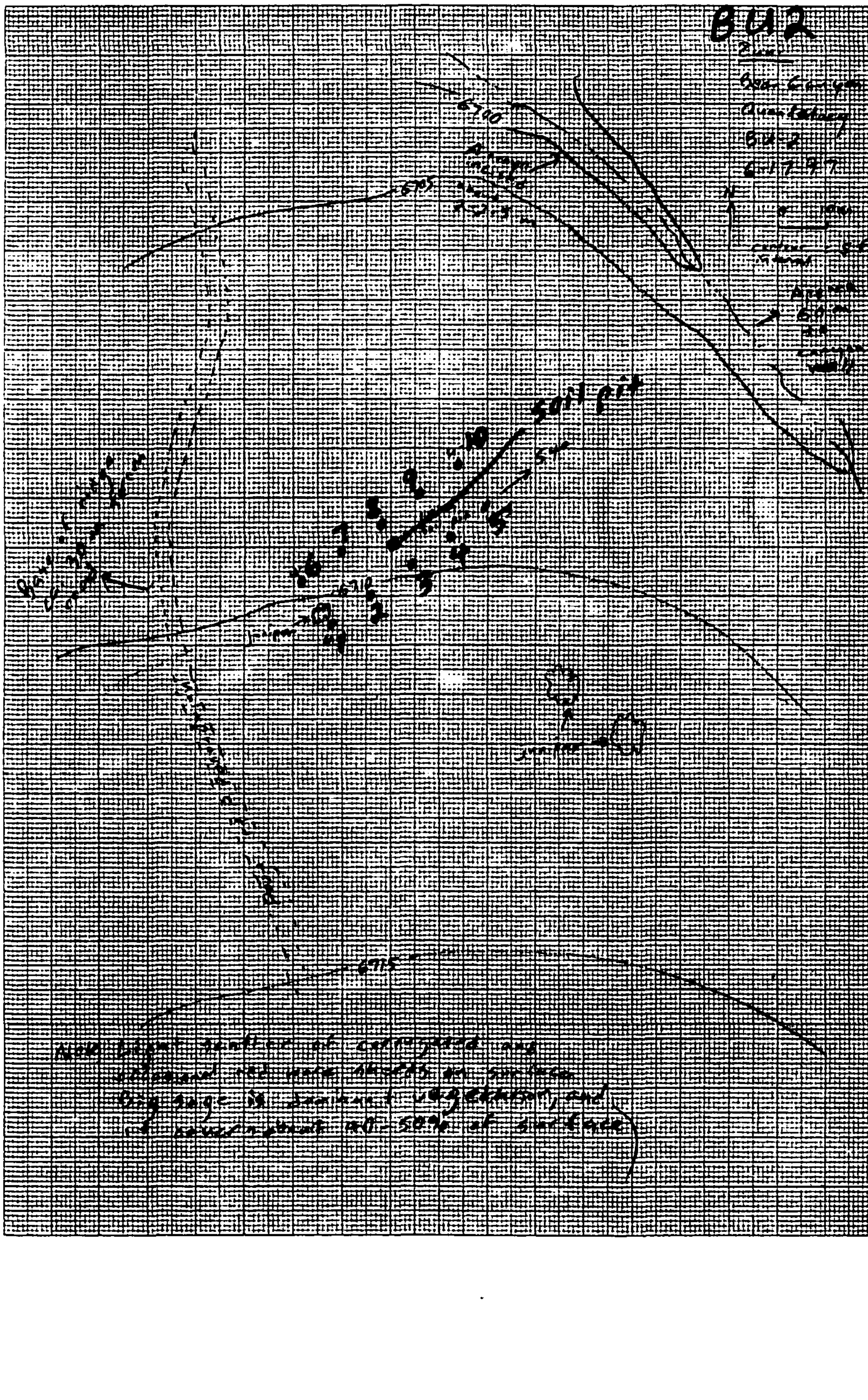
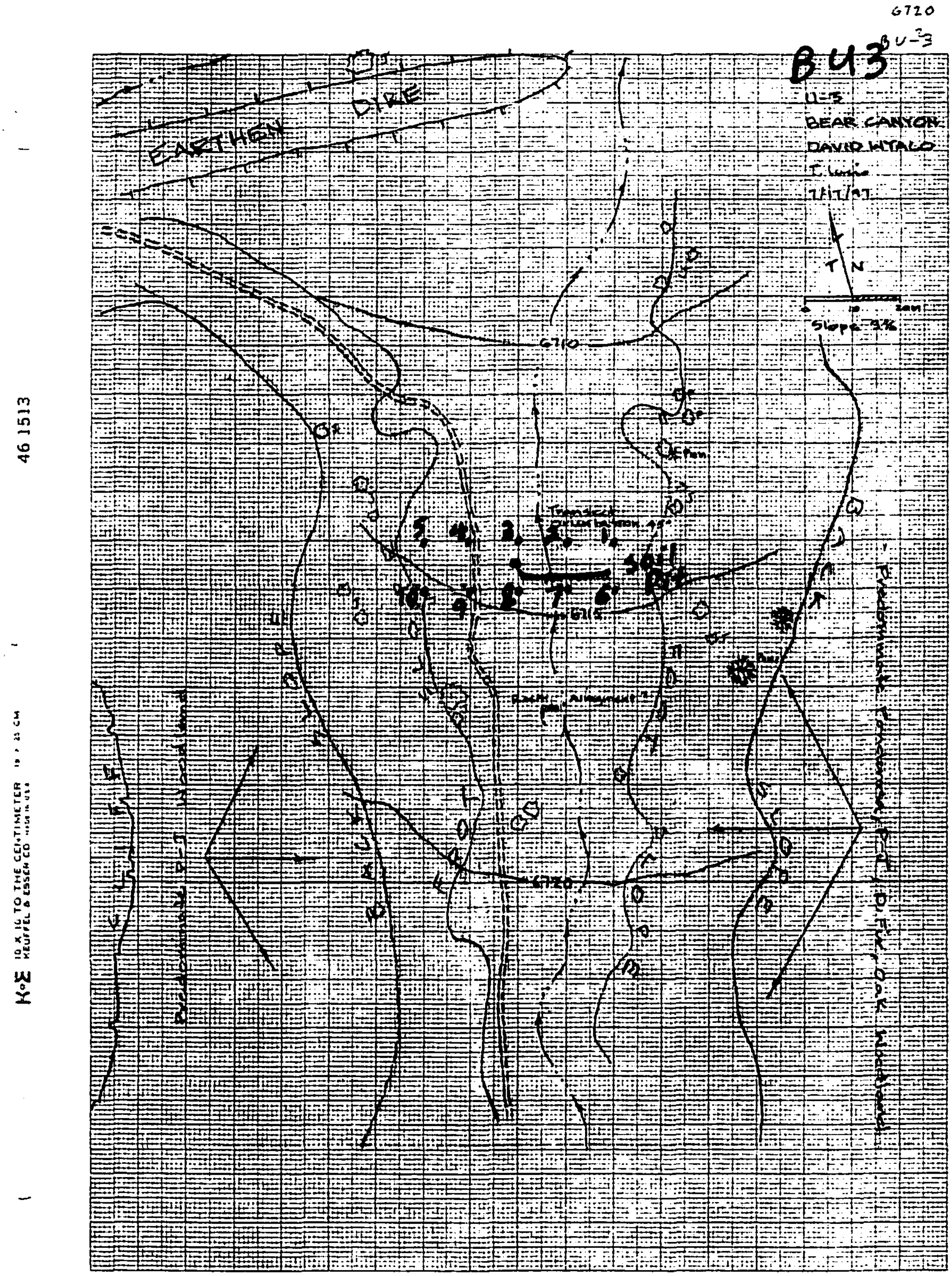
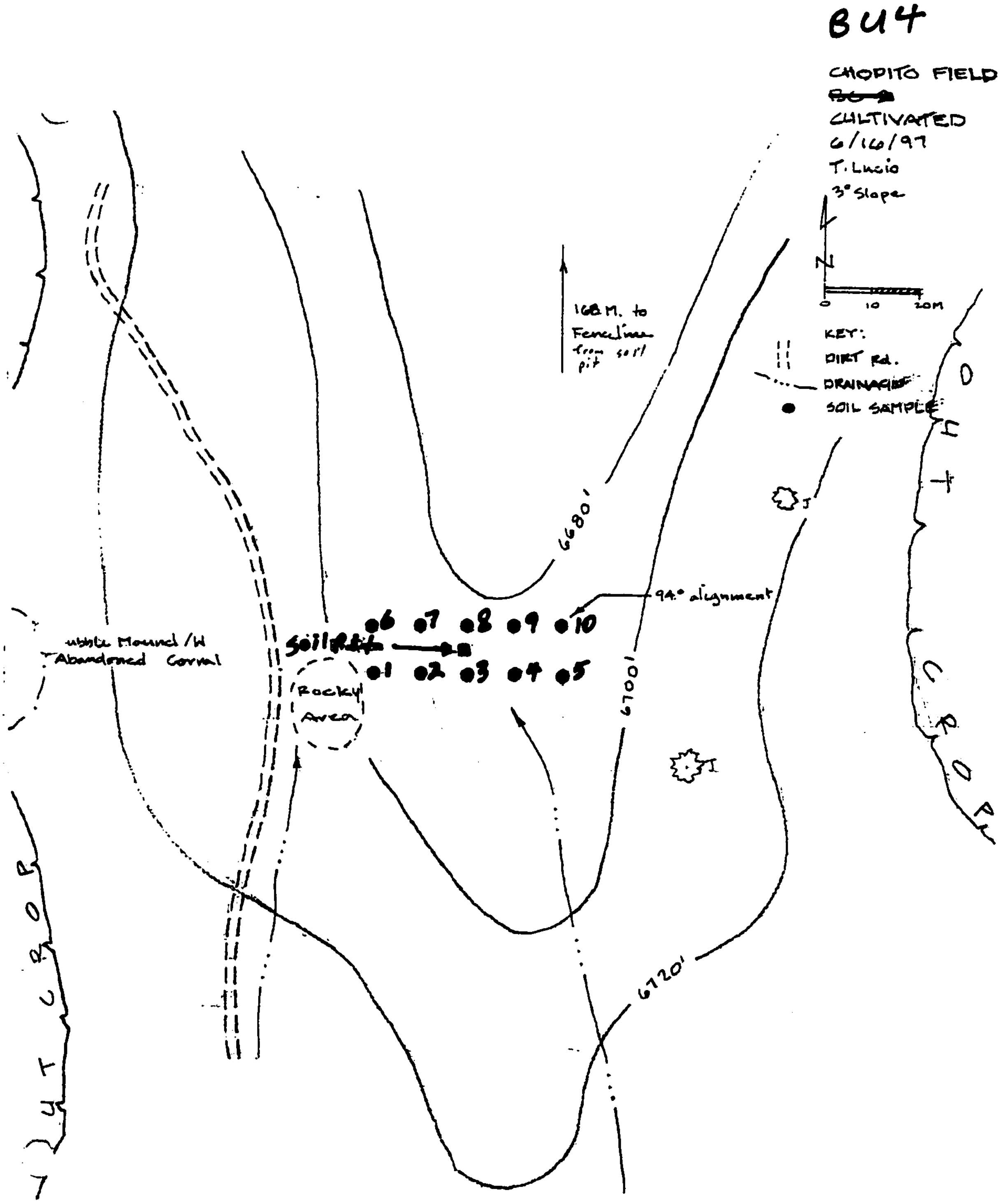

NU3
NU-3
UPPER NUTRIA
7/22/97
N
0 10 20m
Slope 3%
6780'
Transect Orientation @ 75°
#5 #4 #3 #2 #1
#10 #9 #8 #7 #6
6800
6820



BU1
Zuni Soil Study
Bear Canyon
Fred Weekoty
Uncultivated Fan
5-29-97
352°
0
5m
Trey Lucio
Jeff Homburg
ca. contour interval = 2 ft
KEY:
OLD Rd.
JUNIPER
DRAINAGE
SOIL SAMPLE
6874 ft.
6872 ft
6870
6870 ft
6868 ft.
6866 ft.
6
7
8
9
10
1
2
3
4
5
Soil Pit
Catchment Excavated Mechanically
Sage
Cover

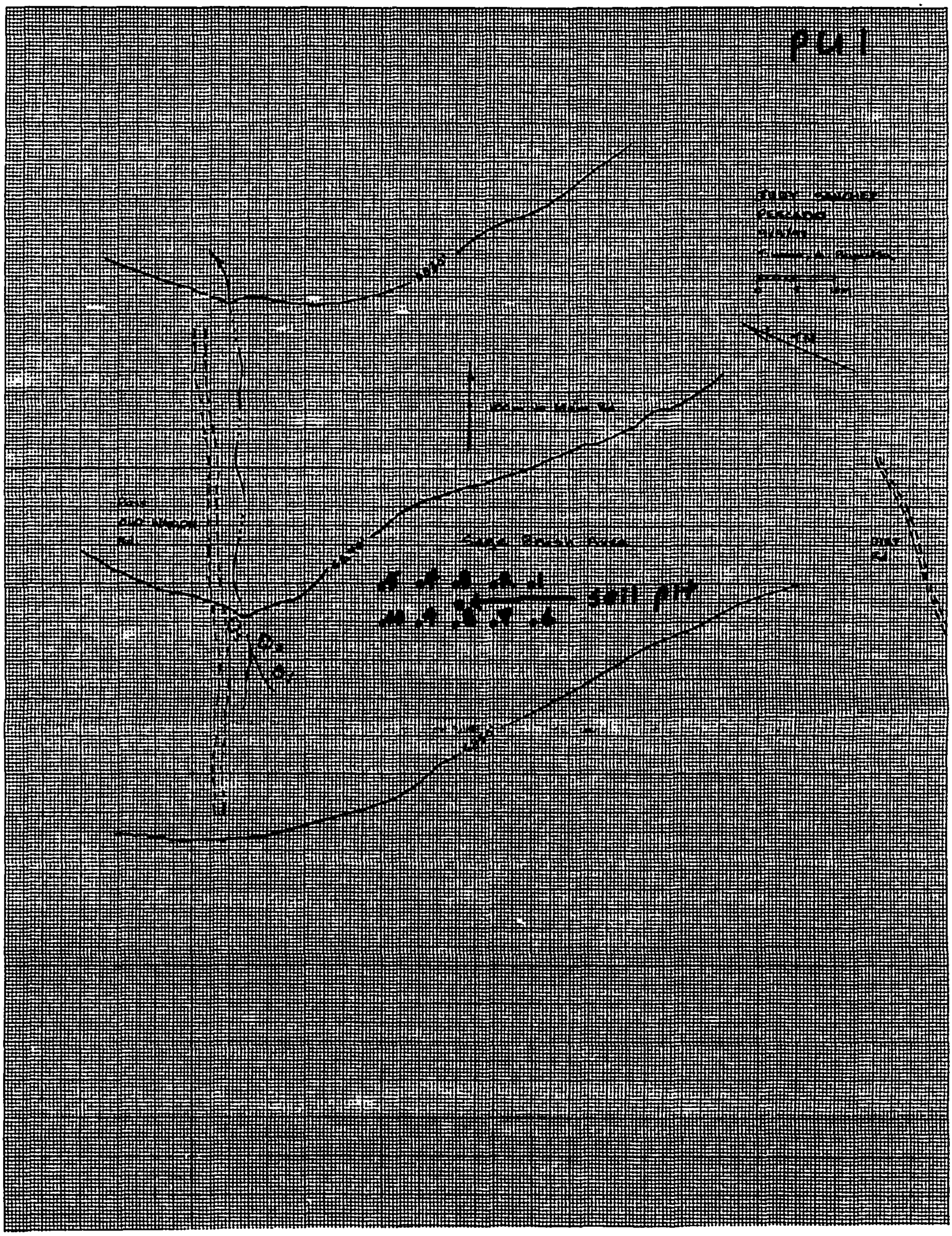

BU2
BU-2
6-17-77
N
soil pit
6700
6705
6710
6715

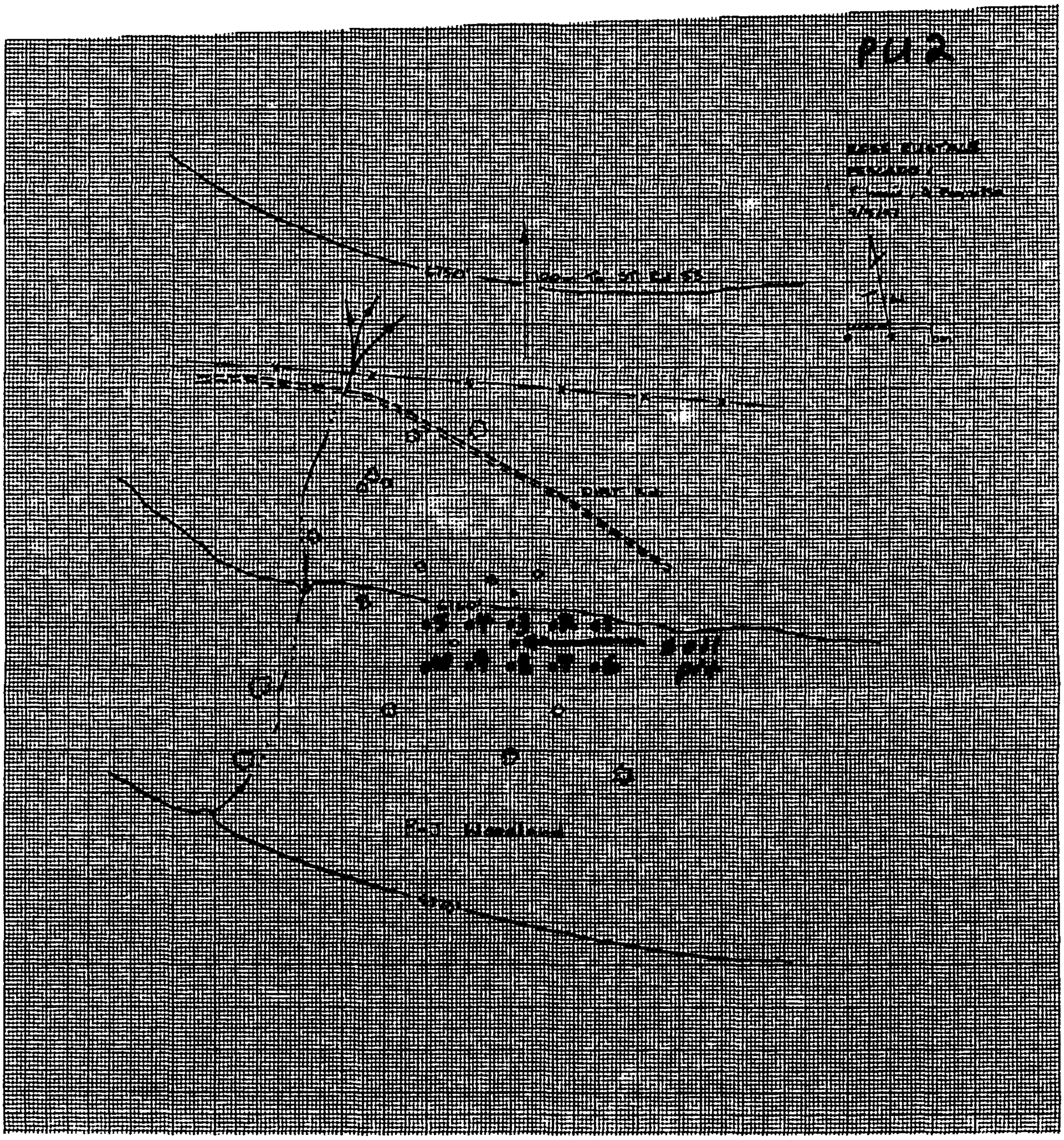

6720
BU3
BU-3
11-5
BEAR CANYON
DAVID WITALO
7/17/97
TN
Slope 3%
EARTHEN
DIKE
6710
6715
6720
46 1513
K&E 10 X 10 TO THE CENTIMETER
KEUFFEL & ESSER CO.

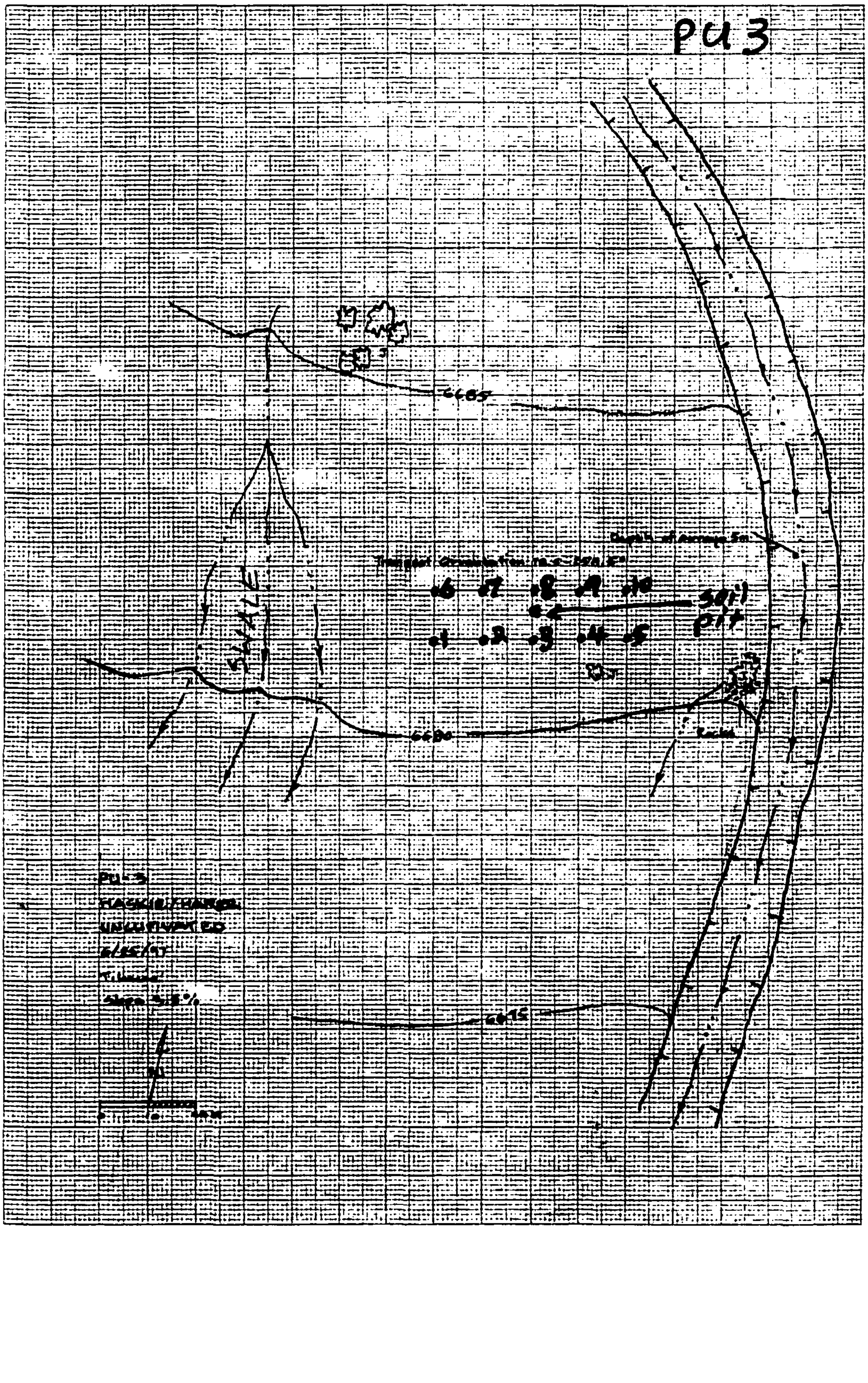

BU4
CHOPITO FIELD
CULTIVATED
6/16/97
T. Lucio
3° Slope
N
0 10 20M
KEY:
DIRT Rd.
DRAINAGE
SOIL SAMPLE
168 M. to Fenceline from soil pit
6680'
6700'
6720'
94° alignment
6 7 8 9 10
1 2 3 4 5
Soil Pit
Rocky Area
Abandoned Corral
OUTCROP
OUTCROP

NO. 3410-M DIETZGEN GRAPH PAPER
MILLIMETER

DIETZGEN CORPORATION
MADE IN U.S.A.




PU 2



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K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM KEUFFEL & ESSER CO.

VITAE

NAME OF AUTHOR: Jeffrey Allan Homburg

NAME AND PLACE OF BIRTH: January 30, 1957, Oklahoma City, Oklahoma

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- B. A. in Anthropology, University of Oklahoma, 1979
- M. A. in Anthropology, Louisiana State University, 1991

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- Marquis Who's Who in Science and Engineering (1993-99), and Who's Who in the West (1993-97)
- Biographee in: Dictionary of International Biography (1994), Men of Achievement (1994-95)
- Gilbert Altschul Fellowship, Statistical Research, 1996
- Miller Fellowship, Iowa State University, 1996-99

PROFESSIONAL EXPERIENCE
- Archaeologist, Archaeological Research and Management Center, University of Oklahoma, 1978-79
- Instructor, Department of Health, Physical Education, and Recreation, University of Oklahoma, 1979-80
- Archaeologist, Museum of the Great Plains, 1980
- Crew Chief and Project/Lab Director, New World Research, 1980-84
- Research Assistant, Department of Geography and Anthropology, Louisiana State University, 1984-87
- Project Director/Geoarchaeologist/Soil Scientist, Statistical Research, 1988-96, 2000-present
- Research Assistant, Department of Agronomy, Iowa State University, 1996-99

SELECTED PUBLICATIONS

Homburg, J.A. 1988. Archaeological Investigations at the LSU Campus Mounds Site. *Louisiana Archaeology* 15:31-204.

Homburg, J. A. 1992. Soil Fertility Study. In *Archaeological Investigations at Lee Canyon* , edited by S. M. Whittlesey. SRI Tech. Series No. 38: 145-161.

Altchul, J. A., R. Ciolek-Torrello, and J. A. Homburg. 1992. Late Prehistoric Change in the Ballona Wetland. In *Archaeological Investigations of Some Significant Sites on the Central Coast of California* 37:89-108. Edited by H. Dallas, Jr. and G. S. Breschini, Coyote Press, Salinas, CA.

Homburg, J.A, J. H. Altschul, and R. Vanderpot. 1994. *Intermontane Settlement Trends in the Eastern Papagueria* (2nd Ed.), SRI Tech. Series No. 37, 431 p.

Homburg, J. A. 1994. Soil Fertility and Prehistoric Agriculture in the Tonto Basin. In *The Roosevelt Rural Sites Study*, Vol. 3, edited by R. Ciolek-Torrello and J. R. Welch, SRI Tech. Series No. 28: 253-295.

Homburg, J. A. and D. D. Ferraro. 1997. Soils and Stratigraphy of the Elsinore Site. In *Continuity and Change*, edited by D. Grenda. SRI Tech. Series 59: 47-76.

Homburg, J. A (editor). 1997. *Vanishing River: Landscapes and Lives of the Lower Verde Valley: The Lower Verde Archaeological Project.* Vol. 2: *Agricultural, Subsistence, and Environmental Studies.* CD-ROM. SRI Press, Tucson. (Alluvial Geomorphology and Geoarchaeology of the Lower Verde River, pp. 17-32, Johnson, W. C., A. F. Arbogast, and J. A. Homburg; Prehistoric Dryland Agricultural Fields of the Lower Verde, pp. 103-126, J. A. Homburg; An Agronomic Study of Two Classic Period Agricultural Fields in the Horseshoe Basin, pp. 127-148, J. A. Homburg and J. A. Sandor).

Ciolek-Torrello, R, J. A. Homburg, and C. Van West. 1999. Paleohydraulic Reconstruction of the Sunset Mesa Canal, Potential Maize Yields, and Population Estimates. In *Investigations at the Sunset Mesa Ruin*, edited by R. Ciolek-Torrello, E. K. Huber, and R. B. Neily. SRI Tech. Series No. 66: 277-280.

Homburg, J. A. 2000. A Biographical Sketch of John Wesley Powell (1834-1902) and His Contributions to the Earth Sciences. *Soil Survey Horizons* 40(1): 1-6.