Anthropogenic Influences on Zuni Agricultural Soils

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Farmers in the Zuni area of the semiarid American Southwest have successfully cultivated maize and other crops for over three millennia without using artificial fertilizers. Zuni agricultural fields are among the oldest, more or less continuously cultivated areas in the United States. Traditional Zuni agriculture is based on runoff farming, a system whereby runoff and organic-rich sediment generated in small watersheds are captured and directed onto fields for crop use. We conducted a study to compare soil properties associated with paired and unpaired cultivated, abandoned, and uncultivated fields to evaluate the long-term effects of cultivation on soil quality. Sampling and analytical methods of this research are especially applicable to geoarchaeological studies of anthropogenic effects on soil fertility and agricultural sustainability in ancient and traditional historical farming systems. Results of the Zuni soil study indicate that cultivation has altered some soil properties, including bulk density, organic carbon, total nitrogen, and C:N ratios in paired fields, but there is no indication that agricultural soils are degraded. This assessment supports the perception of Zuni farmers that long-term cultivation has not caused a decline in agricultural productivity. © 2005 Wiley Periodicals, Inc.

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). Given such limited time perspective on anthropogenic soil changes, there is a need for geoscientists to study the oldest farming systems of the New World, those of Native Americans (for some exceptions, see Doolittle, 2000; Sullivan, 2000; Glaser and Woods, 2004; Lehmann et al., 2004). To help fill this data gap, we studied soils associated with an American Indian agricultural system in a semiarid region of west-central New Mexico (Figure 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 agricultural practices that are very similar to those used prehistorically. This study has important methodological and theoretical

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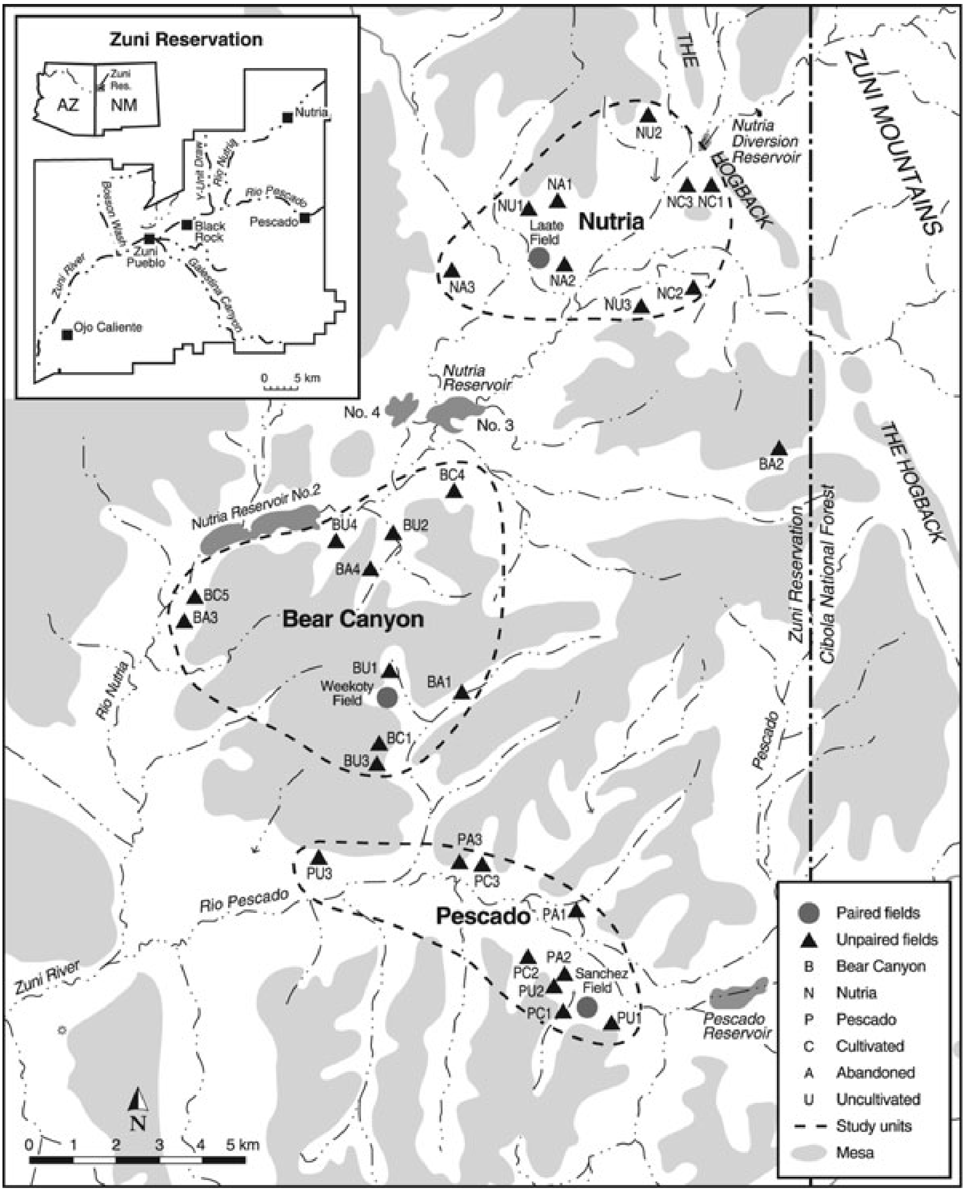

Figure 1. Location of the Zuni Reservation and paired (intensive) and unpaired (extensive) fields.

implications for how ancient agricultural soils and anthropogenic effects can be sampled and evaluated in archaeological contexts. The soil-sampling approach and suite of soil tests used to measure soil quality are directly applicable to geoarchaeological studies of ancient agricultural soils.

Overcoming low water availability is usually viewed as the major hurdle to achieving agricultural sustainability in the semiarid Southwest, both today and in the past. This 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 in understanding the agroecology of farming systems in the Southwest, where productivity is not limited by water alone (Ludwig, 1987). Nitrogen deficiency, in fact, 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, 1984; Sandor and Gersper, 1988). Cultivation of crops with high nutrient requirements, such as maize, heightens this problem by depleting already low nitrogen stores (Stevenson, 1982; Doolittle, 1984; Loomis and Connor, 1992:Figure 12.1).

Research objectives of the Zuni soil study are to: (1) characterize the chemical and physical properties of agricultural soils; (2) identify and assess soil and geomorphic factors important to the functioning of runoff fields; and (3) determine if long-term cultivation has altered the quality of 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 (Figure 1).

We attempted to hold nonanthropogenic soil-forming factors as constant as possible by focusing soil sampling on similar elevations, landscape positions, and geologic contexts. Soil samples were collected from alluvial fans and a few colluvial footslopes, mainly at elevations of about 2070 m and in watersheds smaller than 150 hectares. Sampling concentrated on map units of the Hosta soil series (Aridic Haplustalf), a widespread soil where many runoff fields are located in the eastern part of the reservation.

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. 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, 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. For the purpose of this study, cultivated fields are defined as those that are either currently farmed or left fallow within the last decade, and that have been plowed mechanically since about World War II. Abandoned fields include pre-1940s fields that were tilled using horse-drawn plows and then left fallow. These fields were identified based on archival records and interviews with Zuni farmers. Uncultivated fields are ones lacking archival evidence of farming activity over the last century. Archaeological traces (e.g., agricultural rock alignments, remnants of masonry field houses and farmsteads, and a granary) of Pueblo II period (A.D. 1050–1150) farming activity were found at many fields we sampled (Homburg, 2000).

BACKGROUND DISCUSSION

The Zuni and Runoff Farming

The Zuni, who now number over 9000 people, are one of the Western Pueblo tribes of the Southwest (Eggan and Pandey, 1979; Woodbury, 1979). 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 modern reservation boundary (Ferguson and Hart, 1985). Zuni and other American Indian groups of the semiarid Southwest have a long tradition of runoff farming. Zuni agricultural fields are among the oldest, more or less continuously cultivated lands in the United States. Macrobotanical remains of maize were radiocarbon-dated to about 2270 $\pm$ 70 yr B.P. (Beta-25998) (Rhode, 1990:49) on the Zuni Reservation. Evidence of early agriculture, including irrigation canals dating to 2000–3000 yr B.P. (Late Archaic and Basketmaker II periods), was found during recent archaeological projects (Damp and Kendrick, 2000; Damp et al., 2002) in Y Unit Draw and on the Zuni River floodplain near Black Rock (see Figure 1).

Significantly, even today Zuni farmers do not rely on artificial fertilizers, and that makes the present study especially applicable to many geoarchaeological studies of prehistoric farming systems. Instead of applying artificial fertilizers, Zuni fields are fertilized naturally with organic-rich sediments carried in runoff water (Norton, 1996, 2000; Homburg, 2000; Homburg et al., 2000; Norton et al., 2003; Sandor et al., in review). Runoff farming is an agricultural system that involves capturing runoff and sediment from watersheds and directing them onto agricultural fields (see Figure 2a). This type of agricultural system takes advantage of natural erosion in the watershed and field placement in areas of deposition (Lowrance, 1992). Earthen berms, rock alignments, wooden dams, and shallow ditches are commonly built to control erosion and divert runoff across fields for crop use. Frank Cushing was the first to document the effectiveness of Zuni techniques in spreading water and organic-rich sediment across an agricultural field (Cushing, 1979; reprint of writings first published in 1884).

A number of studies of ancient and historical Zuni agriculture were undertaken many decades later (e.g., Bohrer, 1960; Kintigh, 1984, 1985; Ferguson, 1985; Ferguson and Hart, 1985; Graham, 1990; Brandt, 1992, 1995; Prevost et al., 1993; Manolescu, 1994; Cleveland et al., 1995; Hart, 1995; Havener, 1999; Maxwell, 2000; Damp et al., 2002). Most of these studies, however, do not focus on soil properties and anthropogenic effects associated with Zuni agroecosystems. Rhode (1990, 1995) modeled productivity and water use for traditional Zuni farming systems, and Pawluk (1995) interviewed Zuni farmers to document their knowledge and concepts of agricultural soils and organic-rich sediment. Pawluk learned of *tanayan sowe* ("tree soil"; Figure 2b), a Zuni term that shows that farmers clearly recognize the crucial role of organic-rich sediments in nutrient renewal, especially debris from decomposed juniper litter (Pawluk, 1995; Sandor et al., 2002). Norton (1996, 2000) and Norton et al. (1998, 2002, 2003) investigated the hydrology of Zuni fields and demonstrated the importance of small watersheds in supplying water and nutrients to Zuni fields. The importance of small watersheds for runoff farming has been reported by a number of studies in the Southwest (McGee, 1895; Bryan, 1929; Stewart, 1939; Stewart, 1940a, 1940b; Hack, 1942; Nabhan,

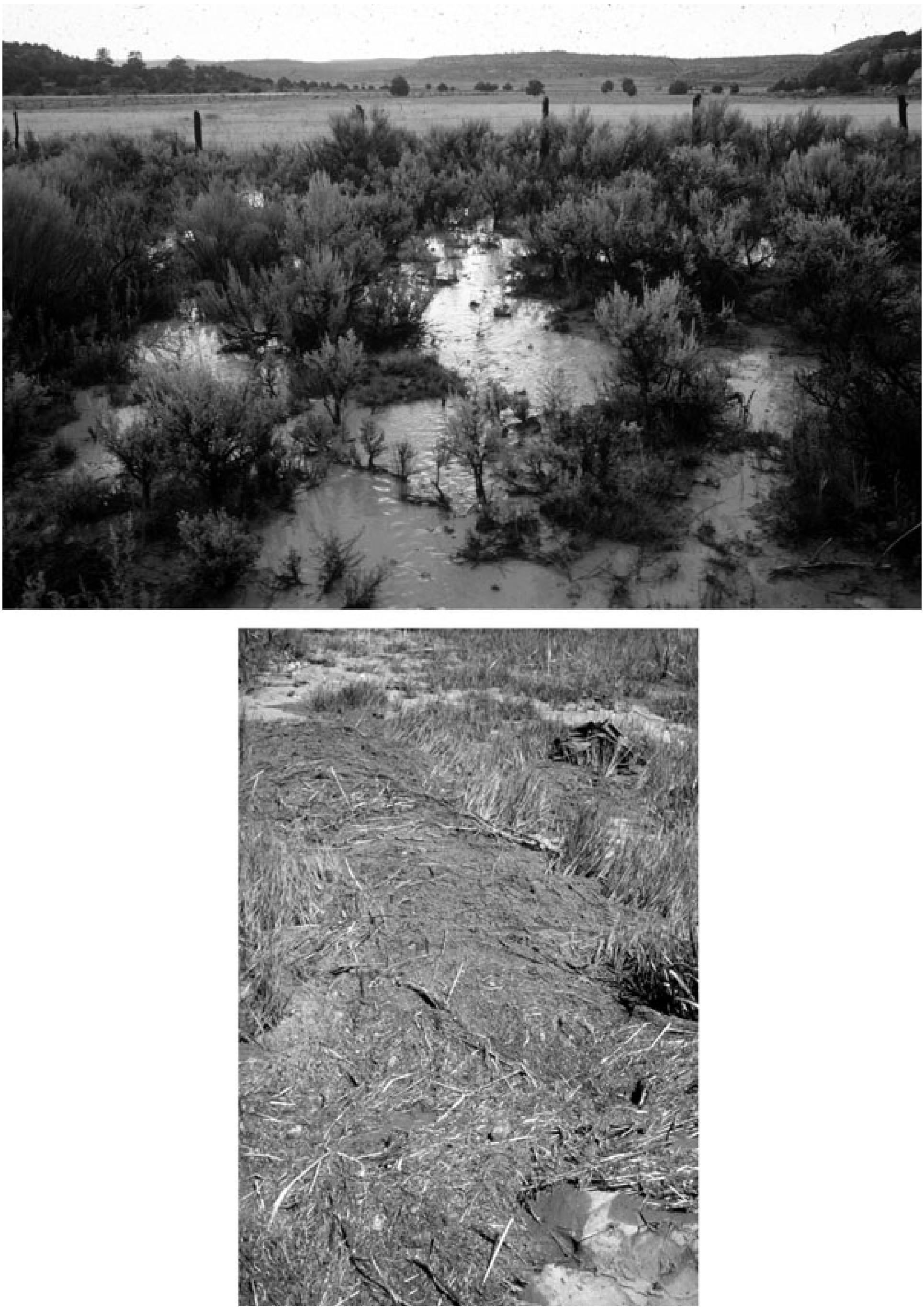

Figure 2. (a) Floodwater draining into a field during a runoff event; (b) Organic-rich sediment delivered to alluvial fan by runoff.

1979, 1983, 1984, 1986a, 1986b) and other desert settings around the world (Parr, 1943; Boers and Ben-Asher, 1982; Evenari et al., 1982; Bruins 1986, 1990; Bruins et al., 1987; Kowsar, 1991; Cohen et al., 1995; Lavee et al., 1997; Niemeijer, 1998). Muenchrath et al. (2002) found that maize productivity in modern Zuni fields is highly variable but averages 572 (SE $\pm$ 181) kg/ha (see Schroeder [1999, 2001] for comparative data on maize productivity in Native American fields in North America). Sandor et al. (in review) investigated the biogeochemistry and agroecology of traditional Zuni runoff fields placed in valley-margin and canyon settings, and noted that alluvial fans and footslopes are productive settings for agriculture because: (1) runoff water and nutrients are naturally concentrated; (2) the growing season is extended because cold-air drainage effects are decreased relative to valley bottoms; and (3) potential salinization effects are less than on irrigated valley floors.

Previous Soil Studies of American Indian Farming Systems

Few soil studies of American Indian farming systems have been conducted, and most of these were based on very small sample sizes or were focused on ancient, abandoned systems lacking continuity to the present. Ancient agricultural soils of the Southwest are well suited for geoarchaeological 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 remain detectable for long periods, probably on time scales of at least 1000 years (Sandor et al., 1986). A few soil studies in the Southwest have found that ancient farming systems degraded the quality of agricultural soils. For example, long-term cultivation significantly lowered the fertility of terraced fields in the Mimbres area (Sandor, 1983, 1995; Sandor et al., 1986, 1990), and farming practices at prehistoric fields near Flagstaff, Santa Fe, and at Mesa Verde tended to deplete phosphate and other nutrients to levels that made fields unproductive and caused them to be abandoned (Arrhenius, 1963). Other studies in central Arizona, especially studies of rock mulch agriculture, have not found that soils were degraded, and, in fact, soil productivity was often enhanced (Homburg, 1994; Homburg and Sandor, 1997, 2002, 2004). The few soil studies conducted thus far in the Southwest indicate that the consequences of agriculture are highly variable in terms of soil fertility and 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).

Rationale for Tests Used in This Soil Study

To document soil properties and assess anthropogenic effects of Zuni agriculture on soils in runoff fields, we measured long-term indicators of soil quality and sustainable land use, focusing on soil morphology, organic matter, and nutrients. A common outcome of long-term agriculture is degradation, whereby anthropogenic changes in soil properties cause a decline in agricultural productivity (Dale and Carter, 1955; Butzer, 1982; Hillel, 1991). Many studies of modern and ancient agri-

Table I. 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 or bedrock.
Soil structure	Macromorphology: lowered grade of granular or subangular blocky structure, trend toward massive state, especially in surface horizons. Commonly caused by compaction and organic matter decline. Micromorphological thin sections used to compare structure and pore types 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 aeration, 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	Sodic soil conditions are recognized by high exchangeable sodium and high pH. Sodic and/or saline soils can be prevalent in agricultural fields of arid and semiarid regions. Detrimental effects on many plants, including crop species, occur both through direct chemical effects and through soil structural deterioration.

cultural 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).

Paired-site sampling provides a way to infer soil changes resulting from agriculture. Potential statistical difficulties in paired-site studies and their validity are recognized (Hurlbert, 1984), but this widely used method can yield valuable information. Paired site comparisons are one of the few available means for evaluating anthropogenic changes in ancient agricultural soils (Sandor and Eash, 1991). To strengthen statistical comparisons of agricultural and uncultivated soils, we used both paired (intensive) and unpaired (extensive) sampling methods.

Each soil property measured is important for crop productivity, and soil changes were interpreted in this study by common criteria for assessing soil degradation (Table I). These properties are derived from the *minimum data set* and other properties commonly recognized as key indicators of soil quality (Larson and Pierce, 1991, 1994; Arshad and Coen, 1992; Pappendick and Parr, 1992). We recognize that soil quality, how it is measured, and exactly what should constitute a minimum data set are not without ambiguity. Still, given the paucity of previous research on Zuni agricultural soils, this minimum data set encompasses a range of basic soil characterization that is useful for evaluating soil quality.

There is no agreement on a single definition of soil quality, and some researchers have questioned the validity of the soil-quality concept (Sojka and Upchurch, 1999). Mausbach and Seybold (1998:33) note that soil-quality definitions range from simply *the capacity of a soil to function* (Pierce and Larson, 1993) to more inclusive ones, such as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1996, 1997:6). We agree with Kimble's (1998:44) assertion that "[t]here 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, the soil properties examined by this study are valid measures for evaluating soil degradation, even though precise thresholds of what constitutes soil degradation are debatable.

Study Area

The study area is located on the southeastern Colorado Plateau, about 35 km west of the continental divide. Principal drainages in the eastern part of the reservation include Rio Nutria and Rio Pescado, which join to form the Zuni River (Figure 1), a tributary of the Little Colorado River. The soil parent material consists chiefly of Quaternary alluvium weathered from Cretaceous sedimentary rocks, including sandstone, siltstone, mudstone, and shale from the Gallup Sandstone and Crevasse Canyon formations (Orr, 1987; Anderson et al., 1989). Alluvial fans formed in, or downslope of, canyons cut into rocky mesas. Soil textures vary over short distances due to natural vertical and horizontal stratification processes on these fans and differences in geologic strata in the watersheds. Unpublished soil maps, produced by Steve Parks of the National Resources Conservation Service, show that Hosta soils are represented on many alluvial fans. The Hosta series, revised in March 1998, encompasses 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 1–8% slopes and elevations of 6600–7500 feet (2012–2286 m). The Hosta series is classified at the family level of Soil Taxonomy (Soil Survey Staff, 1999) as fine, mixed, superactive, mesic, Aridic Haplustalfs. Our soil sampling concentrated on areas mapped as the Hosta series, but many pedons in the study do not meet the criteria of the Hosta series.

The climate of the eastern part of the Zuni Reservation is temperate and semiarid, with annual precipitation averaging about 300 mm. 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. Snowmelt is an important source of soil moisture for crops after planting, and summer monsoons commonly supply moisture in the latter half of the growing season. Farming success often depends on receiving at least two or three storms to water the fields, and the amount, intensity, and timing of these events is critical for agricultural production. In many or even most years, nonirrigated farming in the Zuni area would be impossible without supplemental water from runoff (Kintigh, 1985). Rain during the growing season often consists of localized, torrential downpours. Spatial and temporal variability in rainfall is extremely high in the Zuni area, so farmers commonly spread their fields across different soils, landforms, and watersheds 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 (*Juniperus spp.*) and pinyon (*Pinus edulis*) woodlands. Ponderosa pine (*P. ponderosa*) and Gambel's oak (*Quercus gambelii*) are common on cool, moist, north-facing slopes in the Pescado and Bear Canyon study areas. Cryptogamic crusts and nitrogen-fixing plants, such as mountain mahogany (*Cercocarpus montanus*), deer vetch (*Lotus wrightii*), and scurfpea (*Psoralea tenuflora*), are widespread in many upper watersheds, and these may play an important role in supplying nutrients to agricultural fields below.

FIELD AND LAB METHODS

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 ones that were not; (3) reviewing archival data compiled by Graham (1990) on individual fields; and (4) seeking recommendations from local farmers knowledgeable of the land-use history of agricultural 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 were abandoned for several decades, and uncultivated fields in similar settings that lack evidence of historical farming activity. It was more difficult to find suitable fields for the extensive sampling program, and, in some cases, we sampled all or most of the candidates that met our sampling design criteria; that is, runoff fields with similar landforms, watersheds, elevations, and soils, and with well-documented land-use histories.

Three intensively sampled cultivated and uncultivated field pairs were included in the sampling design. Twenty-nine unpaired (extensive) fields were selected for sampling, divided between 9 cultivated, 10 abandoned, and 10 uncultivated fields. At each paired and unpaired field, 10 soil samples were collected from the upper 15 cm, which approximates the depth of plowing. 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 at each field. Four auger holes were placed at the corner soil-sampling points to obtain additional 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 0.75–1.5 m, and the soil profile was described and sampled (see Homburg, 2000: Appendix A for pedon descriptions). Sketch maps were drawn to depict soil-sampling points in relation to topography, rock outcrops, roads, archaeological sites, and other geographic features (see Homburg, 2000: Appendix C for the sketch maps). Morphological properties (e.g., depth, color, texture, structure, and consistence) were described, and soil horizons were designated in accordance with procedures of the soil survey manual (Soil Survey Division Staff, 1993).

Twelve soil micromorphology samples were collected from the upper 10 cm, including two cultivated and two uncultivated samples from each of the three intensive fields. Micromorphology analysis focused on quantifying structural aggregate and pore types by point-counting at 20× with a step interval of 300 micrometers. Slides were also scanned at scales ranging from 10× to 100× in order to document selected pedo- and biological features (e.g., clay and organic matter coatings, iron oxides, fecal matter, and plant residues) and to search for differences between cultivated and uncultivated soils, using terminology recommended by Bullock et al. (1985).

Soil analyses of bulk samples included particle-size, bulk density, pH, organic carbon, nitrogen, and total and available phosphorus. Particle-size distributions were determined using the sieve and pipette method (Gee and Or, 2002: Methods 2.4.3.2 and 2.4.3.4), with samples pretreated with 30% hydrogen peroxide 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 (Grossman and Reinsch, 2002: Method 2.1.4). Soil pH was measured electrometrically in a 1:1 suspension (weight basis) of soil and distilled/deionized water (Thomas, 1996). Total carbon and nitrogen concentrations were determined by dry combustion using a Leco CHN-600 Elemental Analyzer (Nelson and Sommers, 1996: high-temperature induction furnace method). Total carbon content was assumed to be identical or very similar to organic carbon levels because of the near to total absence of carbonates. Total phosphorus was measured using an alkaline oxidation extract (Dick and Tabatabai, 1977), and available phosphorus was determined using the Olsen extraction method (extract of 0.5 M $NaHCO_3$ at pH 8; Olsen and Sommers, 1982: Method 24–5.5.20; Kuo, 1996).

We used one-way analysis of variance (ANOVA) to test for statistical differences between cultivated and uncultivated soil samples from each pair of intensive fields. Paired *t*-tests were used to test for overall differences between the paired cultivated and uncultivated fields. One-way ANOVA was used to test for differences between extensive fields, using a randomized block design with treatments consisting of soil-management types (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 sample, the unit of analysis for the extensive study was the mean of 10 samples from each field. We analyzed 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 of three paired fields, based on recommendations of Dr. Philip Dixon, statistician at Iowa State University.

RESULTS AND DISCUSSION

Soil Classification and Morphology

Soils in the three intensive fields were classified in three different soil orders (Table II). Pedons in the Laate field in the Nutria study area are Entisols with high clay content and a possible buried argillic horizon. Recent sedimentation accounts for the lack of surface pedogenic development in the Laate field. Pedons of the Sanchez field in the Pescado study area are Alfisols marked by minimally developed argillic horizons, and pedons in the Weekoty field in the Bear Canyon study area are Mollisols. Subgroup designations for soils in the extensive fields are compared to the intensive fields in Table III. The 29 extensive fields include 18 Alfisols (62%), 8 Inceptisols (28%), 2 Entisols, and 1 Mollisol (see Table II). It is noteworthy that most Inceptisols (63%) have Bt horizons but lack enough illuvial clay to qualify as Alfisols. For agricultural purposes, Inceptisols (Aridic Haplustepts) are very similar in soil development and texture to most Alfisols (Aridic Haplustalfs) in the study area. The presence of Bt horizons is probably a critical factor in successful runoff farming at Zuni and elsewhere in the Southwest. Argillic horizons mark the most frequent wetting zone, and they hold moisture in the rooting zone for long periods after rainfall. Argillic horizons in the Sanchez and Weekoty fields had plant-available moisture capacities that were 57% higher than those of overlying topsoils. Similarly, elevated plant moisture capacities were also documented in argillic horizons in the Carrizo Wash drainage system located about 100 km south of the Zuni study (Homburg and Casey, 2004; Casey and Homburg, 2005). Sandy loams and loams are the dominant soil textures in the Zuni soils, followed by clay loams, silty clay loams, sandy clay loams, and, rarely, clays and silty clays. The loamy soils are well suited for cropping because of their ability to supply moisture and nutrients to plant roots.

Soil micromorphology supports the assessments of soil structure made macroscopically with hand specimens in the field, enabling us to quantify anthropogenic influences on soil structure. Figure 3a depicts the better granular development of the uncultivated Sanchez soil compared to its cultivated counterpart, where disruption caused by plowing has resulted in more massive structure (Figure 3b). Granules do exist in the cultivated soils but with less frequency. The trend toward more massive microstructure in cultivated soils was repeated in all fields (Figure 4).

An important finding of the profile descriptions is that A horizons tend to be thicker and Bt horizons deeper in the cultivated soils (Figure 5). Topsoil thickening in the Zuni cultivated fields is explained, in part, by plowing that has mixed the upper BAt horizon into the overlying A horizon, thus producing a thickened Ap horizon. But plowing is insufficient for explaining the thickening, because the thickness often exceeds the

Table II. Taxonomic soil classification and landform associations for intensive and extensive fields.

Fields *	Soil Order	Soil Family	Landform
Intensive Fields			
Laate, Cult.	Entisol	Fine-loamy, mixed, mesic, Aridic Ustifluvents	Distal fan/alluvial plain
Laate, Uncult.	Entisol	Fine-loamy, mixed, mesic, Aridic Ustifluvents	Distal fan/alluvial plain
Sanchez, Cult.	Alfisol	Fine-loamy, mixed, mesic, Aridic Haplustalfs	Middle fan
Sanchez, Uncult.	Alfisol	Fine, mixed, mesic, Aridic Haplustalfs	Middle fan
Weekoty, Cult.	Mollisol	Fine-loamy, mixed, mesic, Aridic Argiustolls	Middle fan
Weekoty, Uncult.	Mollisol	Fine-loamy, mixed, mesic, Aridic Argiustolls	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

approximate 15-cm depth of plowing, so sedimentation must play an important role in the thickening as well. Supporting this interpretation is our observation of laminated zones within some plow zones (that is, in Ap/C horizons), which clearly shows

Table III. Summary of soil subgroups of intensive and extensive fields.

	Intensive Fields		Extensive Fields			
Soil Subgroup	Cultivated	Uncultivated	Cultivated	Abandoned	Uncultivated	Total
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

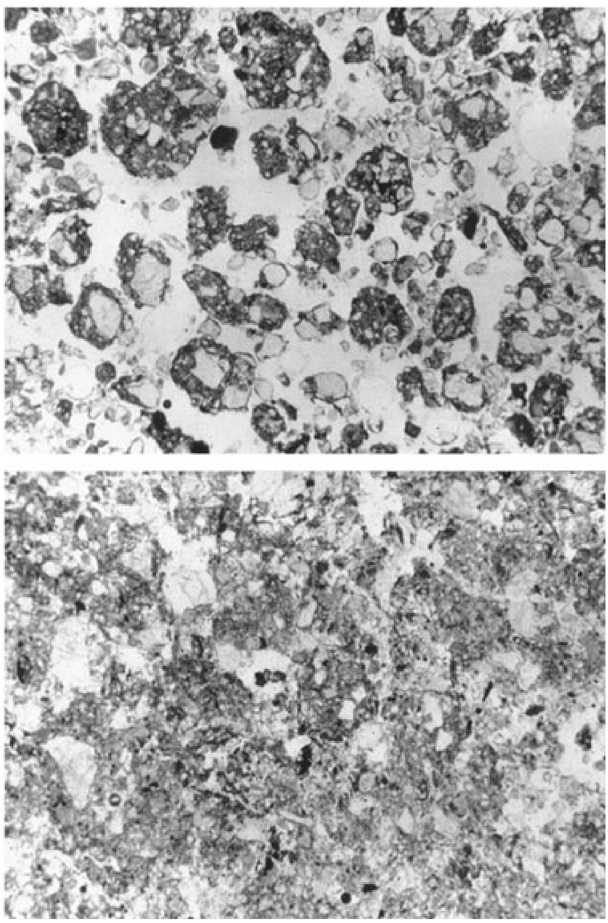

Figure 3. Photomicrographs of soils from the Sanchez field: (a) granular structure of uncultivated soil; (b) massive structure of cultivated soil (all samples from 0–10 cm depth; scale: frame length = 7 mm for all photos). Each stacked bar represents a mean of two samples analyzed by point counting at 300-µ interval.

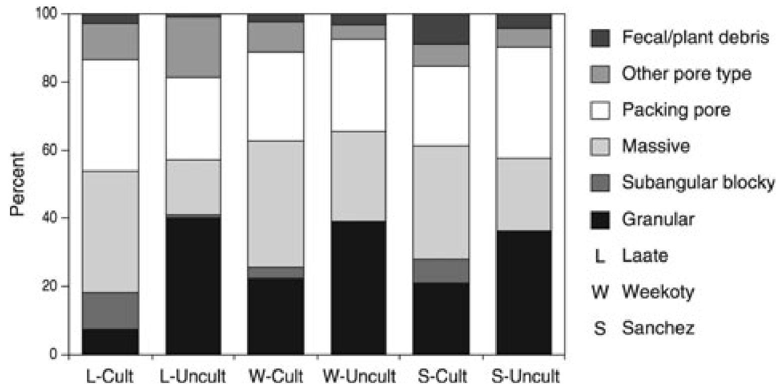

Figure 4. Comparison of solid and pore volumes, and structural aggregate and pore types, in soils of intensive fields.

that sedimentation is contemporaneous with the timing of farming in these fields. Nutrient-rich organic debris is commonly carried in runoff water from the upper watershed and incorporated in laminated alluvium. 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 nutrient renewal process.

Physical and Chemical Soil Properties

A total of 595 bulk soil samples were collected and analyzed, with 360 samples from the 0–15 cm sampling points (70 from the intensive and 290 from the extensive fields) and 235 samples from soil profiles and augers (55 from the intensive and 180 from the extensive fields). Data for the individual samples and means for intensive and extensive fields are shown in Tables IV and V, respectively. Means are shown graphically for the chemical and physical tests in Figures 6 and 7, along with standard deviations above the mean. Overall, statistical differences between intensive cultivated and uncultivated fields are shown by *t*-tests in Table VI.

Increased pH was found in many comparisons of uncultivated and agricultural contexts, due to incorporation of runoff sediment high in bases from the watershed. In contrast to Zuni runoff farming, reduced pH levels are nearly ubiquitous in agricultural systems, especially those dependent on NH_4-N fertilizers because these produce H^+ during nitrification (Tisdale et al., 1993). The Zuni cultivated fields had an average pH of 7.0, which is higher than the pH 6.9 and 6.7 of the abandoned and uncultivated fields, respectively. Increased pH is highly to very highly significant for the Weekoty and Sanchez fields (Table VII). 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 seriously reduce nutrient availability for maize or cause dispersion of soil aggregates. No statistical differences in pH were noted for

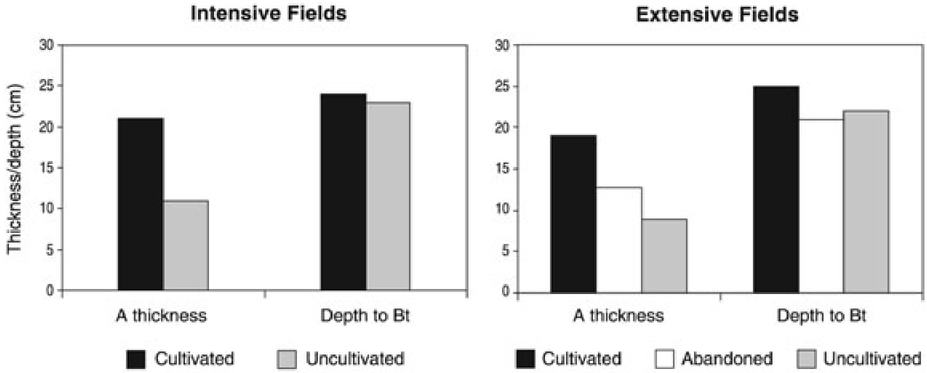

Figure 5. A horizon thickness and depth to Bt horizon in intensive and extensive fields.

the extensive fields, but the same general trends were found, with cultivated soils having the highest pH levels (Table VIII).

Trends in organic C varied between land-use treatments (that is, cultivated vs. uncultivated). No statistical difference was found in organic C by the paired *t*-test for the paired fields as a whole, even though cultivated fields averaged 18% less organic C (on a relative difference, as with percentages in Tables VI and VII) than uncultivated ones. Although a mean difference of 18% was found, high variability exists between fields, and one of the intensive cultivated fields, Sanchez, actually had a 21% increase in organic C, while the Laate field, Weekoty field edge, and Weekoty middle field, had decreases of 25%, 75%, and 55%, respectively (all percentages based on relative differences). The elevated C in the Sanchez field is largely explained by the increased clay content, which, in turn, is a function of both natural sedimentation on the fan and management by farmers to slow runoff and increase deposition on the agricultural field. The only statistically significant difference was found in the Weekoty field, and this decrease in C is explained mainly by the higher sand content in cultivated soils at this field (67% vs. 55%). No significant differences in organic C were found among treatments (cultivated, abandoned, and uncultivated) in the extensive fields.

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 N than uncultivated soils. The statistical differences in N mirror those of organic C in the ANOVA tests for all intensive fields. As with organic C, no statistical differences were found between fields in the extensive treatment. It is important to note that an experiment to compare Zuni blue maize with a drought-adapted hybrid found that both N and P are significantly elevated in the grain of the Zuni cultivar, apparently because this variety of maize is much better adapted to mobilizing these nutrients from the soil to the grain (Homburg et al., 2004; Sandor et al., in review).

Table IV. Soil data for intensive fields.

Field	pH	Org. C (g/kg)	N (g/kg)	C:N Ratio	Av. P (mg/kg)	Total P (mg/kg)	Bulk Density (g/cm^3)	Sand	Silt (%)	Clay
Laate, Cultivated										
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, Uncultivated										
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, Cultivated										
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, Uncultivated										
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**
Wekoty, Cultivated (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**

(continued)

Table IV. (*Continued*)

Field	pH	Org. C (g/kg)	N (g/kg)	C:N Ratio	Av. P (mg/kg)	Total P (mg/kg)	Bulk Density (g/cm^3)	Sand	Silt (%)	Clay
Sanchez, Cultivated										
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, Uncultivated										
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. No P data exist for the Weekoty mid-field position.

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

Field	pH	Org. C (g/kg)	N (g/kg)	C:N Ratio	Av. P (mg/kg)	Total P (mg/kg)	Bulk Density (g/cm^3)	Sand	Silt (%)	Clay
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

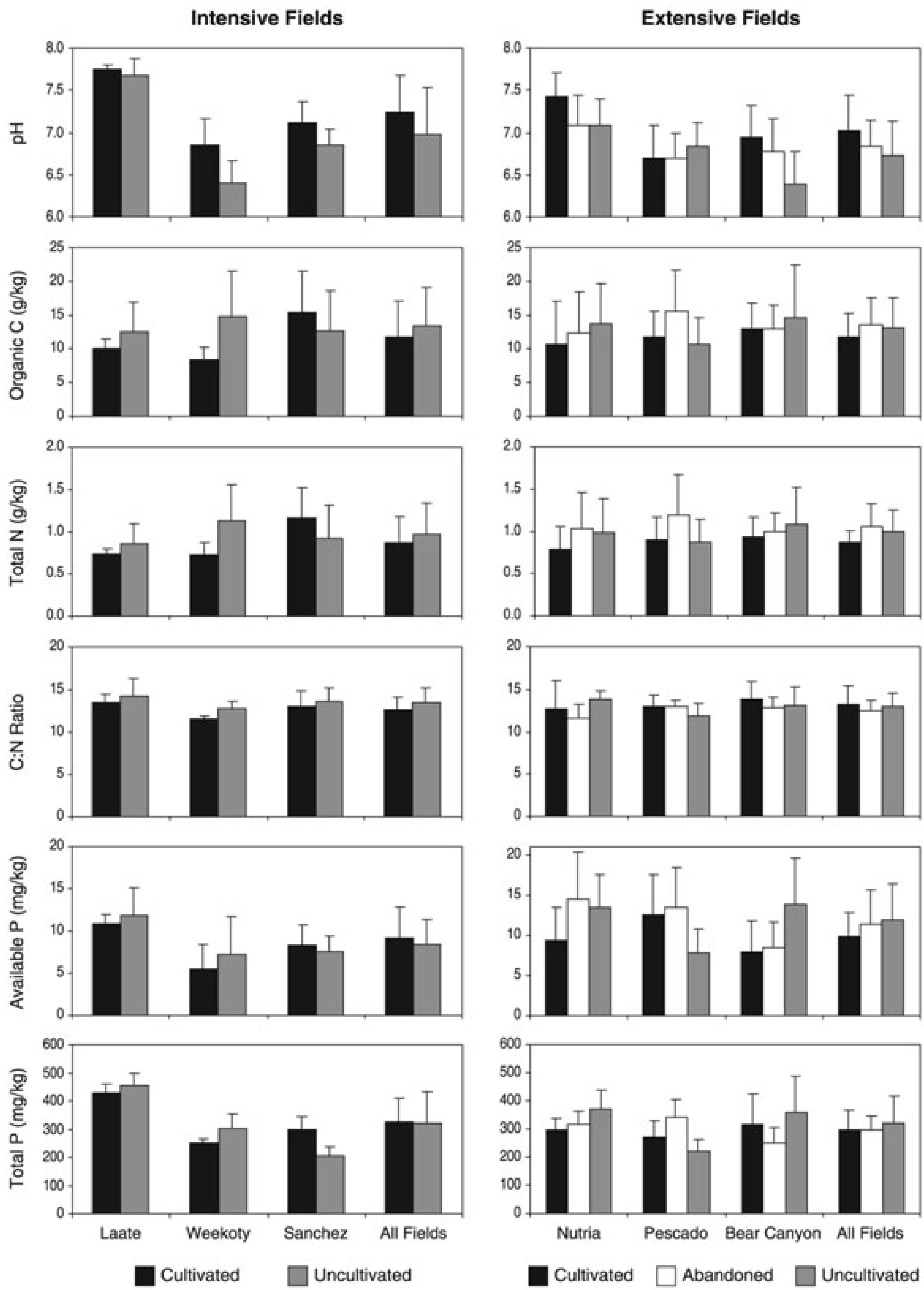

Figure 6. Comparison of pH, C, N, C:N ratio, and total and available P data for intensive and extensive fields. Bars indicate the means and the error bars indicate the standard deviation from the mean.

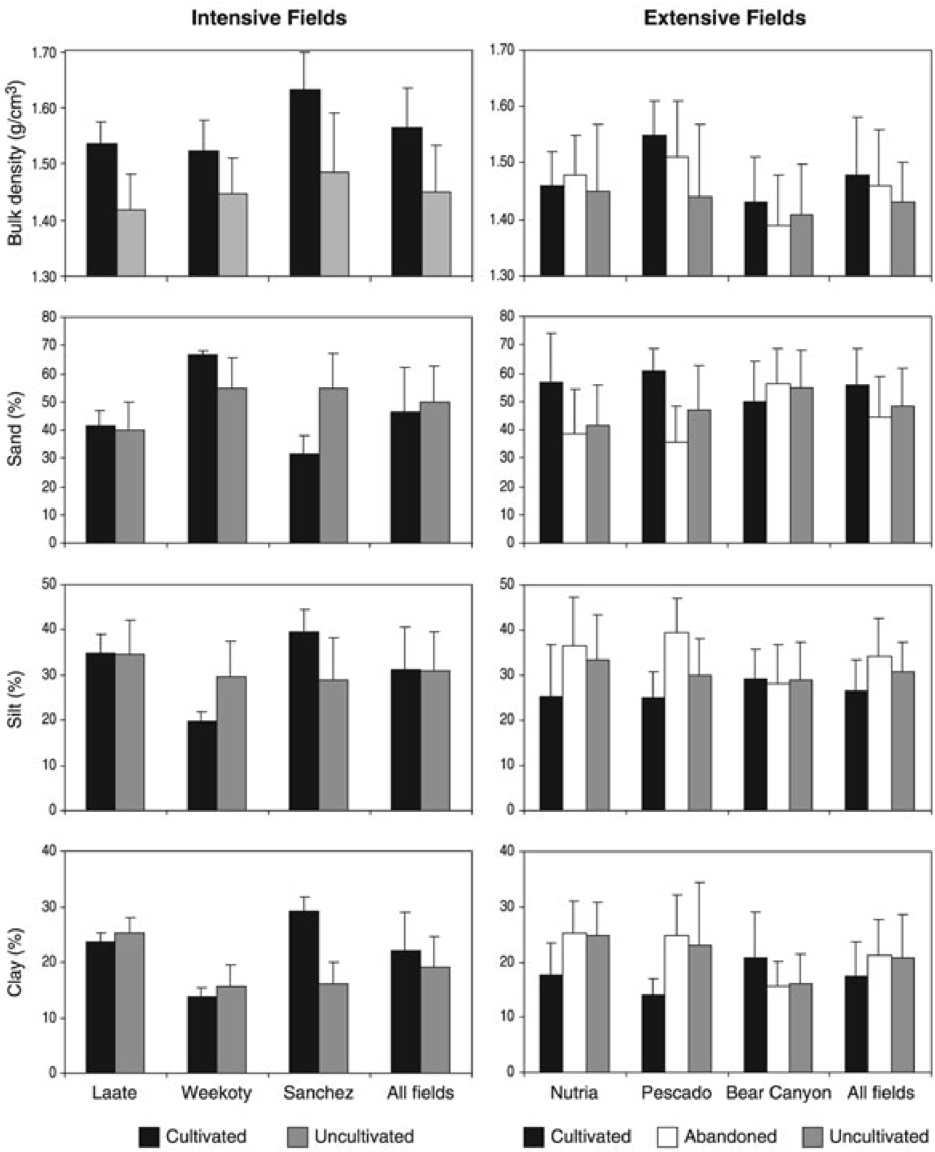

Figure 7. Comparison of bulk density and soil texture data for intensive and extensive fields. Bars indicate the means and the error bars indicate the standard deviation from the mean.

Paired *t*-tests showed that intensive cultivated soils generally 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,

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

Soil Property	Field	Mean for Each Field Cult	Mean for Each Field Uncult.	Mean for All Fields Cult	Mean for All Fields Uncult.	% Diff. of Cult. Fields	P-Value	Significance
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/cm^3)	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; % difference of pH not shown due to log scale of values.

Table VII. ANOVA tests 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/cm^3)	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/cm^3)	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, Mid-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/cm^3)	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.
% difference of pH not shown due to log scale of values.

Table VIII. 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	0.90	6.90	0.40	6.70	1.00	0.17	
Organic C	(g/kg)	12.20	4.90	13.20	5.50	13.10	6.60	0.65	
N	(g/kg)	0.90	0.30	1.05	0.40	0.99	0.40	0.24	
C:N ratio		13.30	2.30	12.40	1.30	13.00	2.50	0.71	
Available P	(mg/kg)	9.50	4.80	11.90	5.30	13.70	5.20	0.46	
Total P	(mg/kg)	294.00	72.00	296.00	50.00	322.00	94.00	0.64	
Bulk density	(g/cm^3)	1.48	0.10	1.46	0.10	1.43	22.00	0.32	
Sand	(%)	56.70	1.90	42.60	16.00	48.60	16.00	0.13	
Silt	(%)	26.50	26.50	35.00	10.30	30.70	9.40	0.08	
Clay	(%)	16.90	8.30	22.40	6.90	20.80	8.90	0.30	

* Significant at 0.05.

a trend that is common in cultivated soils relative to comparable uncultivated soils (Jenny, 1941; Sandor et al., 1986). The lower C:N ratios in agricultural fields are important in this agroecosystem, because as organic debris is altered by microbial decomposition as it moves from the watershed to the fields below, N becomes increasingly available for crop use beyond that required by soil microbes. No statistical differences in C:N ratios were found between treatments for the extensive fields.

No definitive trends were found in available and total P data from both the intensive and extensive fields. Soils of paired cultivated fields averaged 9% less available P and 1% more total P, but neither of these differences are 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 a function of the higher clay content. Similar to organic C and N, available and total P values are slightly reduced in the cultivated soils of the Laate and Weekoty fields, but not at statistically significant levels. Available P is lower in the extensive cultivated soils, but again, not at levels of deficiency and not at statistically significant levels. 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). All Zuni samples exceeded 5 mg/kg, often by a factor of 2, so there is no indication that available P is deficient 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) than the uncultivated controls. The greatest difference, at 9.9% higher, was found in the cultivated Sanchez soils, which averaged 1.64 g/cm^3; the higher clay content in the Sanchez field makes it more prone to compaction than other fields, but its higher clay content also makes it more resilient, so the compaction can be more easily reversed than in sandy soils. No statistical differences were found among treatments for the extensive fields. Bulk density differences averaged only 3.5% in the cultivated versus uncultivated fields (1.48 vs. 1.43 g/cm^3), and there was tremendous overlap in bulk density values for the cultivated, abandoned, and uncultivated fields. This shows that Zuni farmers can successfully cultivate soils of variable bulk densities and that compaction is not a widespread problem at this broader scale of analysis.

To determine if compaction caused degradation, it is necessary to consider the texture. Bulk densities ranging from about 1.60 to 1.85 g/cm^3 can impede root growth, depending on soil texture (Scopp, 2000: Table 1.4). Lab and field studies of compacted clays in Iowa, for example, indicate that maize growth and productivity are highly correlated with compaction levels in the bulk density range of 0.94–1.30 g/cm^3 (Phillips and Kirkham, 1962a, 1962b). The Zuni topsoils, which are predominantly sandy loams and loams that are friable to very friable, probably do not limit seedling emergence. Compaction problems are more likely when plowing wet soils (Soane, 1982), which is not a concern in the semiarid Zuni area. Furthermore, Zuni tractors are light, at less than about 2 tons, which is much lighter than those averaging about 7 tons in modern conventional systems, which are known to cause a number of physical and hydrological problems for agriculture (Cruse and Gupta, 1991). Bulk densities below the plow zone of Zuni soils are highly variable, with most having a similar or lower bulk density, so there is no evidence that a plow pan has formed due to the weight of tractors.

Paired *t*-tests for the intensive fields identified no statistically significant differences between percentages of sand, silt, and clay (see Table VI). By contrast, the cultivated Sanchez field has about 24% less sand, 11% more silt, and 13% more clay than its uncultivated control. Textural differences in this field reflect a combination of natural horizontal variability overprinted by recent natural and culturally modified sedimentation processes in the cultivated fields. 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, probably offer a better way for assessing major anthropogenic influences on soil texture. No statistical differences were identified by the ANOVA tests of treatment effects on soil texture (Table VIII). An examination of soil texture in the extensive fields indicates that there are no consistent trends along gradients of farming intensity, with mechanical plowing being the most intensive, uncultivated treatments the least, and abandoned fields intermediate.

Correlation analyses were undertaken to assess the relationships between soil test variables (Tables IX and X). This analysis focused on comparisons between soil tests to search for connections between these variables. Not surprisingly, there are many statistically significant positive and negative correlations, and several of these were reviewed in the discussion above. Here, we focus on two correlations (organic C vs. bulk density and organic C vs. silt) noted by this and previous studies. Scatter plots of the means and individual samples from the 29 extensive fields are shown in Homburg (2000: Figures 14 and 15). Many studies have shown that organic C and bulk density are inversely related. That is, as organic C declines, bulk density typically increases. By comparison, Sandor et al. (1986) also observed this relationship for uncultivated soils but not cultivated soils. 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

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

	Laate		Weekoty		Sanchez	
Comparison	Cult	Uncult	Cult	Uncult	Cult	Uncult
Org. C vs. sand	–0.95**	–0.79**	0.19	0.91**	–0.50	–0.84**
Org. C vs. silt	0.94**	0.77**	0.13	0.84**	0.72**	0.88**
Org. C vs. clay	0.74**	0.67*	–0.37	0.84**	–0.07	0.46
Org. C 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 0.05; ** Highly significant at 0.01.

not related in a way that is predictable in cultivated fields. Surprisingly, the correlations between bulk density and organic C are positive for cultivated and abandoned soils (see Table X), though not at statistically significant levels. The lack of statistically significant differences is affected, to varying degrees, by spatial variability in 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, as is found in most agricultural systems. This finding supports the interpretation of co-sedimentation of organic matter and silt in the depositional systems of Zuni runoff fields, a trend first identified by Norton (1996) at the Sanchez field. The much larger dataset presented here further demonstrates the important nutrient-renewal process of silt additions in Zuni runoff fields.

CONCLUSIONS

Cultivation has had both positive and negative effects on Zuni agricultural soils, but we identified no evidence that Zuni agricultural soils are degraded. 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 compared to their uncultivated counterparts. Although these differences are often statistically significant, they are not great enough to indicate degradation. Slight compaction at the levels found may, in fact, be beneficial for water retention in the friable soils of this semiarid environment.

Soil texture has such a strong effect on nutrient-holding properties that it is an especially important property in interpreting soil productivity. Textural differences

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

Comparison	Cultivated	Abandoned	Uncultivated
Org. C vs. sand	–0.78**	–0.38	–0.16
Org. C vs. silt	0.88**	0.42	0.26
Org. C vs. clay	0.58	0.31	0.05
Org. C 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
Av. P 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 0.05; ** Highly significant at 0.01.

between cultivated and uncultivated contexts reflect a combination of natural horizontal and vertical variability on alluvial fans, overprinted by natural and cultural sedimentation processes in cultivated fields. This situation presents potential problems with the paired-field approach, and that is one reason that an extensive (unpaired) component was included as a major part of this soil study. In evaluating anthropogenic effects on soil texture and other variables, it is often impossible to hold nonanthropogenic factors constant, or at least approximately so, when so much natural soil variability exists over short distances. Consequently, the risk of pseudoreplication in a sampling design is always present in this type of field study, resulting from collecting soil samples that vary because of factors other than anthropogenic treatments alone. Paired-field comparisons assume that uncultivated samples are valid controls, but this assumption very often may not be met. Indeed, the biggest challenge in this research was 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 consider incorporating both paired and unpaired sampling methods in the future.

Statistical analysis of extensive fields failed to identify significant land-use treatment (cultivated, abandoned, and uncultivated) effects, and that finding strongly supports the hypothesis that soil alterations are not at levels indicative of degradation. A few weak 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 is low, due mainly to natural spatial variability in soil parent materials.

We conclude that Zuni agricultural runoff soils are not degraded. Cultivated soils in paired fields have some hints of slight degradation, but many such differences are better explained by natural textural variability on the alluvial fans rather than anthropogenic influences. The lack of statistical differences and the low magnitude of soil changes in unpaired fields strongly support our interpretation that agricultural soils are not degraded by cultivation. As we develop the theory for improving reconstructions of anthropogenic influences on soil properties in archaeological context, much more comparative research is needed from a variety of agricultural systems and intensities in different environmental settings. We recommend that future geoarchaeological studies aimed at assessing anthropogenic influences on soil productivity use the suite of soils tests on which this study is based as a way to compare and evaluate cultivated soils relative to uncultivated soils. This kind of research is especially applicable to soil studies in desert environments where long-term traces of anthropogenic influence are often preserved.

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