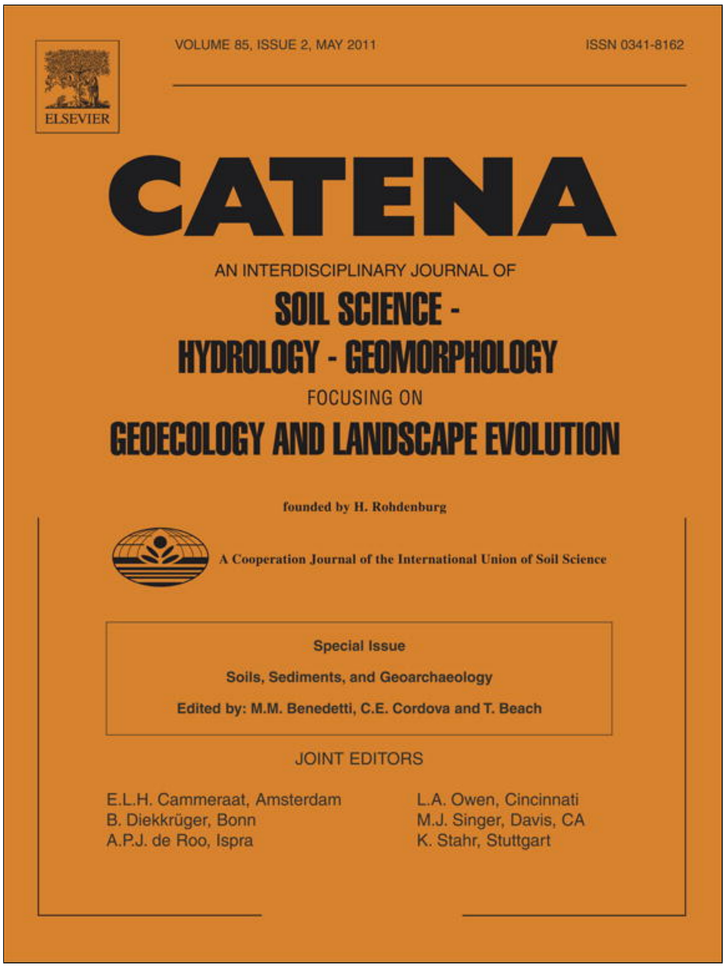

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Anthropogenic effects on soil quality of ancient agricultural systems of the American Southwest

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ABSTRACT

Soil studies of ancient agricultural fields contribute to research on long-term human–environmental relationships and land use sustainability. This kind of research is especially applicable in desert landscapes of the American Southwest because: (1) soil formation is slow enough that cultivation effects persist for centuries to millennia; (2) many ancient fields in valley margins have remained uncultivated since they were abandoned, so long-term soil properties reflect ancient agricultural use; and (3) agricultural features (e.g., terraces, rock alignments and rock piles, and irrigation canals) provide clues for identifying and sampling ancient cultivated and uncultivated soils. Surficial remnants of these field systems persist and remain intact in many cases. Soil studies of ancient and modern American Indian agricultural systems across the Southwest indicate that soil changes are highly variable, ranging from degradation (e.g., organic matter/nutrient decline, compaction), to minimal net change, to enhanced soil quality. Soil changes caused by cultivation can be inferred by comparing soils in agricultural fields relative to reference uncultivated areas in similar landscape settings (that is, space-for-time substitution). Soil response trajectories vary for a number of reasons, such as variability in initial ecosystem conditions, diversity in agricultural methods, variability in the mix of crops and cropping intensity, and environmental sensitivity to alteration (varying resistance and resilience). Studies of rock mulch soils indicate enhanced fertility, with elevated organic carbon, nitrogen, and available phosphorus levels, increased infiltration rates and moisture retention, and no evidence of compaction. By contrast, cultivation effects vary widely for terraced soils. Although numerous studies have focused on irrigation canals, irrigated soils have received far less attention. Soil studies of irrigation systems along the Gila and Santa Cruz rivers of Arizona now underway will help fill this research gap.

1. Introduction

Soils have been subject to change due to agricultural land use in the approximately four millennia since farming began in the American Southwest. The causes of anthropogenic soil changes are complex and wide-ranging in kind, magnitude, and scales of space and time, encompassing many processes and outcomes (Johnson and Lewis, 1995; Sandor et al., 2005). The archaeological record provides a critical long-term perspective on soil changes caused by humans in the past (Holliday, 2004; Sandor and Eash, 1991). The Southwest contains such a record of anthropogenic soil and landscape alteration, with numerous cases of success and failure in maintaining productivity and conserving land resources. Although complex, soil changes can be interpreted on a gradient from enhancement of soil quality to soil degradation, with neutral, mixed, or uncertain outcomes in between. Several themes concerning soil change, and related landscape and ecosystem change, are explored in this paper. For the purpose of this study we define the American Southwest as the region identified by archaeologists that extends from southern Colorado and Utah southward across Arizona and New Mexico and into Chihuahua and Sonora of northwest Mexico.

Diversity is closely linked to how soils, ecosystems, and human societies change and respond to perturbations. Diversity is a hallmark of Southwest American Indian agriculture (Table 1), and is also an indicator of soil, ecosystem, and agricultural integrity and viability. Agricultural diversification, such as coupled irrigation and dryland systems, is a key component of risk management strategies of ancient farmers and farming communities. Likewise, diversity contributes to the stability and resilience of soil resources and ecosystems. Soil degradation commonly involves lowered diversity at several scales (Table 2). Much of diversity loss, such as through decreased organic matter and structural degradation, is an inadvertent consequence of agriculture. However, some agricultural management, especially in modern industrialized systems, deliberately promotes uniformity in physical soil properties and especially nutrient levels through land

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Table 1
Diversity of Southwest agricultural strategies.

Kind of agriculture	Landforms
Irrigated	Valley floodplains/terraces
•Canal	Floodplains/terraces, mostly perennial rivers
•Flood recession	Lower Colorado and Gila Rivers
•Floodwater	Floodplains of ephemeral streams
Dryland	Uplands and valley margins
•Aeolian materials	Loess uplands, stable dunes in valleys and uplands, tephra fields
•Rock grid, mulch, pile	Mostly valley martins, some upland hillslopes
•Runoff terrace	Valley margins (alluvial fans, footslopes), upland hillslopes

leveling, fertilization, and other practices to maximize large-scale crop production.

Ancient farmers of the Southwest and other regions faced problems in environmental resource conservation, as do modern societies. Resource depletion and degradation may be reflected in population movement and land abandonment, which occurred repeatedly in Southwest prehistory locally and regionally (Cordell, 1997). It is also true, however, that values of conservation, stewardship, and reverence toward the earth are basic tenets of religious beliefs and lifeways of many traditional cultures. That peoples such as the Hopi, Zuni, and other agricultural groups persisted in the same places for many generations is a clear indicator that sustainable land use strategies were developed.

2. Sites and methods for studying soil and landscape change

The diversity of American Indian farming systems parallels the Southwest's remarkable environmental diversity (Doolittle, 2000; Minnis and Elisens, 2000; see Table 1). These agricultural systems occur in all Southwest physiographic provinces, especially the Colorado Plateau, southern Basin and Range, and Transition Zone (Fig. 1) (Morrison, 1991). The Colorado Plateau is characterized by plateaus, mesas, deep canyons, and barren badlands, with landscapes dominated by broad valleys, mesas, buttes, cuestas, and a few volcanic landforms. It encompasses about 337,000 km^2 (130,000 mi^2) in the four corners region of Arizona, Colorado, New Mexico, and Utah. It includes the area drained by the Colorado River and its major tributaries, the Green, San Juan, and Little Colorado rivers. The Basin and Range physiographic province is generally characterized by elongated mountain ranges alternating with broad alluvial valleys. The subparallel fault block mountain ranges and valleys mostly trend northwest–southeast or north–south. The Basin and Range covers nearly 800,000 km^2 (300,000 mi^2) and extends from the Great Basin of Nevada, western Utah, and southeast California southwestward into Sonoran Desert section of the southern Basin and Range in Arizona and northwest Mexico. The differences in elevation from the valley floors to the mountain peaks in most Basin and Range areas can range from several hundred feet to over 6000 feet (~1800 m). The boundary separating the Colorado Plateau from the Basin and Range Province is marked by the Mogollon Rim, an erosional cuesta that runs northwest–southeast across Arizona and into New Mexico. This broad Transition Zone below the Mogollon Rim is a rugged mountainous zone where the geologic features are transitional between typical Colorado Plateau and Basin and Range.

Table 2
Spatial scales of anthropogenic soil change (modified from Sandor et al., 2005).

Soil components	Scale (m)	Examples of impacts
Physical, chemical, biological properties (e.g., clay, organic matter, and microbes)	10^{-10}–10^{-4}	Changes in organic carbon and nutrient levels
Macromorphological properties	10^{-3}–10^{-2}	Structure degradation; changes in texture, color, and pores
Horizons	10^{-1}–10^{0}	Erosion or thickening of A horizon; water storage capacity
Whole soils (pedons)	10^{0}–10^{1}	Pervasive changes in organic matter, nitrogen, and phosphorus levels in surface and subsurface horizons
Soil-watersheds-landscapes-ecosystems-biosphere	10^{2} –10^{7}	Broader scale changes in soil distribution, erosion patterns, and vegetation

Within these areas, dryland agricultural sites, including those with rock features in terraced alignments, grids, piles, and mulch, occur in a myriad of geomorphic and ecosystem settings. Irrigated systems occur on floodplain and low stream terraces of major rivers, especially the Colorado, Gila, Rio Grande, Salt, Verde, and their tributaries. Soil studies of American Indian agriculture are few relative to the many agroecosystems that exist, but have been conducted in several environmental settings, in prehistoric to historic to contemporary sites (references in Table 3). Soil studies of ancient agroecosystems in the American Southwest have accelerated since the early 1990s, covering a broad sample of the region. The locations of studies discussed in this paper are shown in Fig. 1. These studies have been funded by traditional research funding sources in the United States (e.g., National Science Foundation and National Geographic Society), but increasingly, archaeological contract studies are funding this research as part of large interdisciplinary archaeological projects conducted to mitigate the effects of proposed developments (e.g., road construction, safety of dams work on reservoirs, construction of coal mines) and other adverse effects (e.g., military jet fuel contamination) on ancient agricultural settlements and associated fields. Although much more research is needed on ancient and contemporary Native American agricultural systems throughout the Southwest, a sufficient body of literature now exists to review the range in outcomes in terms of anthropogenic soil changes caused by agriculture.

Testing for soil change is predicated on the validity of methods. These are a number of potential problems and uncertainties in evaluating long-term effects of agriculture on soils; examples include issues related to: (1) field identification; (2) kind and age of agricultural systems, and impact on soil; (3) post-agricultural environmental change and land use impacts on soils; (4) availability of appropriate uncultivated ("control") soils to use as references for assessing soil change from agriculture; kinds of control soils, their validity, and what can be inferred from them; (5) sample design — number, depth, and type of samples and sample sites needed to test for soil differences; and (6) appropriate physical, chemical, and biological assays of soil properties and how to interpret results (e.g., Holliday, 2004; Homburg et al., 2005; Sandor et al., 1986).

Addressing all these issues is beyond the scope of this paper, but is important to some approaches taken in previous soil studies. We have mainly studied dryland agricultural fields that are readily identified by visible rock alignment and other features that are still intact. These features are usually in valley margin and upland locations without post-agricultural, high impact land use. Most studies have been conducted in prehistoric fields, but we have also investigated historic and traditional contemporary fields, most notably at Zuni, to conduct observational and experimental studies of ancient agricultural fields that have well documented archival records.

The main method for assessing soil change involves comparing identifiable agricultural soils with uncultivated reference or control areas with similar natural soils and geomorphic settings. Most studies referenced in Table 3 rely on comparisons of cultivated and uncultivated control areas to evaluate the anthropogenic effects on soil quality. In a number of cases, however, cultivated soils cannot be clearly differentiated from uncultivated soils; in these situations the

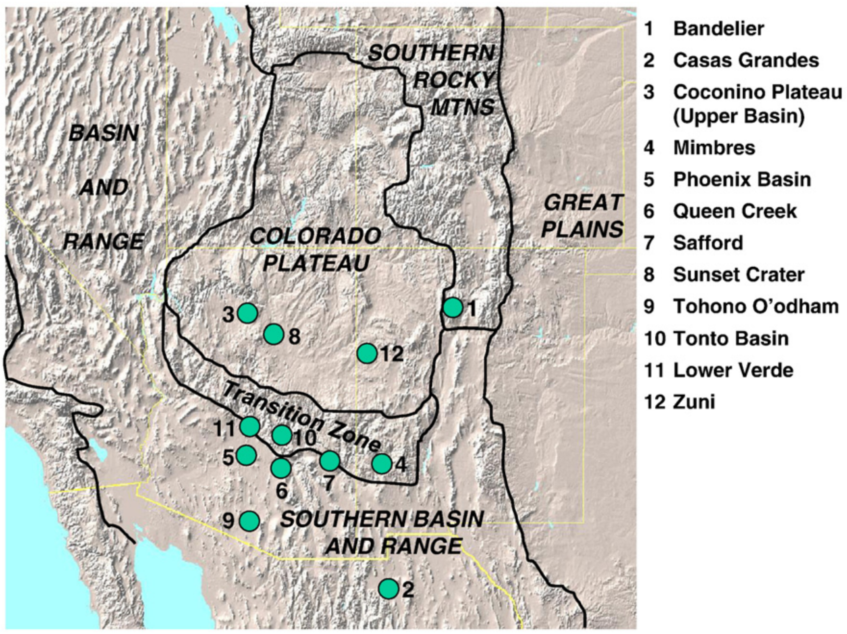

Fig. 1. Soil change research areas in geomorphic provinces of the American Southwest.

general soil quality can be assessed, but the anthropogenic effects of cultivation cannot (for examples, see Homburg, 2000, 2003, 2005). Several basic questions arise concerning uncultivated control areas, the first being what "controls" signify? In effect, we are substituting space for time, with the rationale, or assumption, being that control soils are similar to the original, uncultivated soils. In retrospective studies such as those of ancient agriculture, even if uncultivated soils are available, they are unlikely to precisely represent what original

Table 3
Examples of soil change in Southwest American Indian agriculture by types of outcomes.

Factors/properties	Types of outcomes		
	Positive	Negative	Neutral
	(Enhanced soil productivity, and soil resource protection and sustainability)	(Soil degradation)	(~ No net change, offsetting, mixed, inconclusive or contradictory change, insignificant change, or recovery from degradation)
Soil landscape	Slope stabilization and protection against accelerated water erosion by decrease in slope angle and length	Eroded surface soil, rills, gullies; breached rock alignments; accelerated wind erosion; excessive sedimentation; loss of grass and other vegetation cover. For agroecosystems, maize nutrient deficiency and decreased growth.	Fields showing neither enhancement nor degradation; subtle field features; ecosystem changes.
Physical/morphology	Thickened A horizons/rooting volume with medium texture; increased available water capacity and actual content	Soil erosion, soil structure degradation and compaction, possible soil crusting.	No or insignificant change in bulk density (i.e., no compaction or not enough to be detrimental to crops).
Chemistry	Cases of organic C, N, P increase or replenishment through runoff or irrigation water and sediment; pH optima for nutrient availability; few examples of increase in other nutrients.	Decreased organic carbon, total and available nitrogen and phosphorus.	No or contradictory or insignificant change in organic carbon, soil nutrients, and pH; no definitive data on salt or sodium accumulation in irrigated soils.
Biology	Few direct data; possible increases in nitrogen fixation; increased vesicular arbuscular mycorrhizae in roots of traditional Zuni maize.	Pathogenic fungi in storage room soil possibly associated with maize.	Very little data.
Causes and factors			
Geomorphic/ ecosystem processes	Sedimentation; enhanced desirable post-agriculture native vegetation	Accelerated water erosion, slope instability, undercutting of rock alignments, wind erosion on soil cleared of vegetation and rock fragments.	Not significantly impacted over long-term.
Management	Terracing and rock alignment features; runoff/sediment capture.	Vegetation clearing; inability to manage runoff.	Subtle field construction features and sufficient maintenance.
References	Cushing, 1920; Hack, 1942; Herold and Miller, 1995; Homburg, 2010; Homburg and Sandor, 1997; Homburg et al., 2004; Homburg et al., 2005; Hubbell and Gardner, 1950; Lightfoot, 1990; Nabhan, 1984; Norton et al., 2007; Sandor, 1983; Sandor et al., 1990; Sandor et al., 2007; Schaafsma and Briggs, 2007; Stewart and Donnelly, 1943; Sullivan, 2000.	Dart, 1986; Edwards, 2002; Homburg et al., 2005; Hubbell and Gardner, 1950; Pendleton et al., 2003; Sandor, 1983; Sandor and Gersper, 1988; Sandor et al., 1986, 1990; Stewart and Donnelly, 1943; Sullivan, 2000.	Briggs et al., 2006; Dart, 1986; Huckleberry, 1992; Homburg 1992, 1994; Homburg, 2010; Homburg and Sandor, 1997; Homburg et al., 2004; Homburg et al., 2005; Hubbell and Gardner, 1950; Sandor et al., 2007; Sullivan, 2000.

soils were like prior to cultivation. That is because soils are dynamic bodies that form and change naturally over time. Consequently, soils are palimpsests, reflecting the imprints of environmental change and multiple episodes of land use in the many years between prehistoric agriculture and present observations. To be valid, controls must represent, at least approximately so, what cultivated soils would be like now if they had not been farmed. Because soils vary naturally, even with what appear to be slight differences in geomorphic and ecosystem setting and other soil-forming factors, it is essential to test whether soils being compared are similar enough in their natural properties for a valid comparison. In some areas, finding uncultivated soils to use as controls is very difficult, so other types of comparisons can be made. At Zuni, for example, with its long and continuous agricultural history, nearly all valley edge areas may have been farmed at different times in the past. In that situation, we used historic records of field locations to compare currently cultivated and abandoned agricultural soils with similar soils outside of fields (Homburg et al., 2005).

Our approach in several studies is a combination of "intensive" (that is, paired) and "extensive" (that is, unpaired) comparisons. "Intensive" comparisons involve adjacent cultivated and uncultivated soils; this approach allows more variables to be controlled, thereby allowing as close a comparison as possible. However, if there are not enough paired sample locations across a relatively wide area, there is a danger of pseudoreplication, whereby sample locations are too few and spatially confined to be representative. By contrast, "extensive" comparisons involve sampling more interspersed sites across a broader region, rather than adjacent, paired uncultivated and cultivated sites. This strategy usually allows a greater sample size because of the common difficulty in finding appropriate adjacent sites; the potential downside, however, is a lower probability of controlling enough natural or land use variability, and the possibility of comparing "apples and oranges" (that is, comparing fields that are not truly analogous). Increased background noise may obscure differences that may exist, which can especially be a problem in assessing soils in relatively subtle agricultural systems such as those common in the Southwest.

In summary, there are at least two major challenges in soil change studies of ancient Southwest agriculture: (1) identifying actual fields and soils that were in fact cultivated; and (2) the availability of appropriate uncultivated soils that form the basis for measuring and evaluating soil change. In some situations, there may be other approaches besides the comparative approach for detecting and interpreting soil change, for example dramatic or unique characteristics associated with some agricultural soils whose anthropogenic properties are far beyond the ranges found in natural soils. Despite the methodological challenges, the results of several previous studies indicate that valid information about soil and landscape change can be obtained and interpreted.

3. Soil change processes and interpretations

Soil change caused by agriculture takes many forms, ones that involve feedback among interactive physical, chemical, and biological processes in an array of spatial and temporal scales (Sandor et al., 2005). Soil change is presented in this section in the context of outcomes, based on case studies from the Southwest (Table 3). For heuristic purposes, outcomes can be classified into two extremes, enhanced soil quality versus degradation. It is important to note that such a classification simplifies the real complexity of soil change, changes that in reality occur along a continuum. Between the extremes are intermediate cases that consist of minor, mixed, or inconclusive outcomes. Interpretations of the outcomes are inherently subjective, but are defined here as soil quality and change in terms of (1) sustaining agricultural productivity; i.e., soil function to meet crop needs, and (2) long-term land resource conservation; i.e., maintenance of soil function in ecosystems and the larger environment. The spectrum of outcomes in soil resource condition and productivity is reflected by previous studies of Southwest agriculture.

3.1. Enhanced soil quality

Increased soil quality is most commonly an outcome or at least a goal of deliberate agricultural management. Terracing and runoff agricultural management practices provide a clear example of both direct and indirect beneficial soils and landscape changes. A major kind of dryland agriculture in the Southwest, especially in prehistoric times but also historically, involved a form of terracing associated with runoff agriculture in which small rock alignments were constructed across slopes and drainageways. These constructions modified soils and landscapes in several ways beneficial to crop production and soil conservation (Hack, 1942; Sandor, 2006; Stewart and Donnelly, 1943). By placing rocks to construct terraces, diverse niches were created for farming and managing risk. Terraces serve direct hydrologic and stability functions by segmenting and decreasing slope length, thereby slowing potentially destructive runoff and promoting water infiltration and retention. The indirect natural accumulation of sediment (wedge-shaped in longitudinal cross section) upslope of each dam decreases slope angle (Leopold and Bull, 1979). Reduced slope gradient also helps create a more stable topographic platform for planting crops. The beneficial effects of small terraces have been documented in Southwest locations such as Zuni and Mimbres (Bohrer, 1960; Sandor et al., 1990).

As the sediment wedge becomes incorporated into soils: (1) A horizons are thickened, thereby improving the soil rooting medium and increasing moisture storage capacity; (2) geomorphic stability is increased; and (3) nutrients are replenished and stored for crop use. Increased A horizon thickness measured in Southwest runoff systems ranges from just a few centimeters to nearly a meter, depending mostly on the height of the terrace dam. Given that most rock alignment terraces in the Southwest are low, commonly just one stone high or with just a few courses, most thickening is in the 5–30 cm range. By contrast, constructed soil thicknesses in multi-coursed agricultural terraces are commonly much greater, typically 0.3 to 1.3 m high, and up to 2–3 m in the Andes (Sandor, 2006). Similar thicknesses are found in a few Southwest areas with high cross-drainage check dams, such as those in northern Mexico (Doolittle, 2000; Herold, 1965). Surface soil horizon thickening is also reported for other rock features such as rock piles, probably involving trapping of aeolian sediment (Fish, 2000) or deliberate placement of redeposited soil material or sediment. In addition to soil surface thickening, texture is also an important factor, as loamy to sandy sediments favor water infiltration, ease root growth, and in the case of sandy and gravelly sediments, provide a mulch layer that increases soil water storage for plants by reducing evaporative water loss. In Hohokam floodwater fields, deliberate soil-building through managed deposition of silt-rich sediments was inferred by Schaafsma and Briggs (2007).

At Zuni, surface horizons in some runoff fields on alluvial fans are clearly thickened relative to adjacent areas off the field, even without construction of stone alignments (Homburg et al., 2005; Sandor et al., 2007; Fig. 2). Remnants of terrace alignments, probably constructed of wood and brush or earthen berms rather than stones only, are visible on the ground and in 1935–1937 aerial photos. Short wood posts that likely anchored ephemeral dams occur in association with runoff and floodwater fields. Another important factor is that fields are placed at positions of maximum natural deposition on alluvial fans, so soil surface thickening results from a combination of natural and enhanced sedimentation. Soil A and B horizons buried by this sediment are apparent in some fields. Deliberate field placement and management to capture loamy to sandy sediments and replenish soil nutrients, as well as knowledge of geomorphic processes, is evident in field location

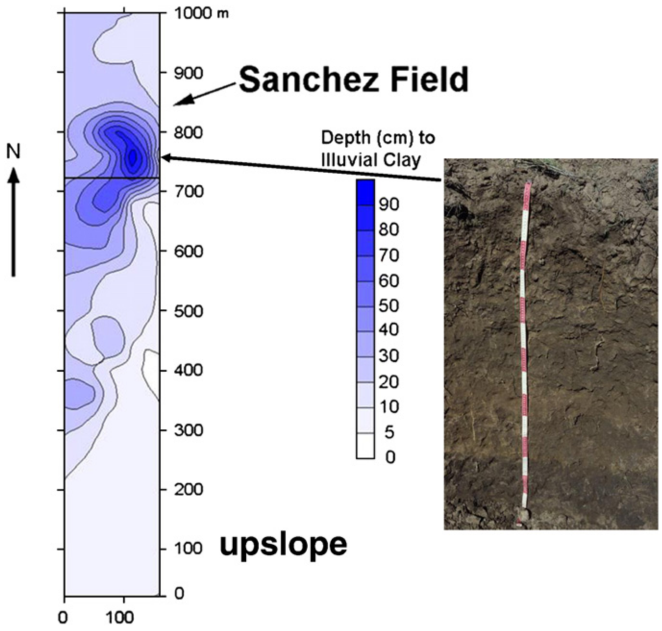

Fig. 2. Soil A horizons are thicker in Zuni runoff fields than uncultivated areas due to: (1) placement of fields in deposition zones of alluvial fields, and (2) long-term management practices (e.g., construction of earthen berms, rock alignments, and brush structures) to slow runoff and promote deposition in field areas. The uncultivated area is south of the fence line at 725 m north. The depth to illuvial clay is indicated by the dark-colored soil in the lower 30+ cm of the photograph.

patterns and ethnographic studies with traditional farmers at Zuni and elsewhere (e.g., Bohrer, 1960; Cushing, 1920; Fish and Fish, 1997; Nabhan, 1984; Norton et al., 2001; Pawluk, 1995; Sandor et al., 2007). Furthermore, organic matter coatings on mineral grains function to renew soil fertility naturally via sedimentation on alluvial fans in the Zuni runoff fields. The addition of organic matter in grain coatings is clearly indicated by soil micromorphology thin sections of A horizons of Zuni fields (Fig. 3). Organic matter is strongly associated with silt-size particles in Zuni fields, which indicates co-sedimentation of silt and organic matter (Homburg et al., 2005).

A horizon thickening is especially effective in conjunction with the widespread use of soils with naturally slowly permeable subsurface horizons and layers, such as argillic horizons, petrocalcic horizons, duripans, stratified sediments, and bedrock (e.g., Dominguez and Kolm, 2005; Edwards, 2002; Homburg et al., 2004, 2005; Sandor et al., 1986; Sandor, 1995). These horizons have the advantage of retaining water above them, and in the case of argillic horizons and clay-rich strata, within them. While petrocalcic horizons, duripans, and bedrock block root penetration, their functional advantage as water retention features is realized when naturally shallow A horizons that serve as root zones are thickened due to sedimentation.

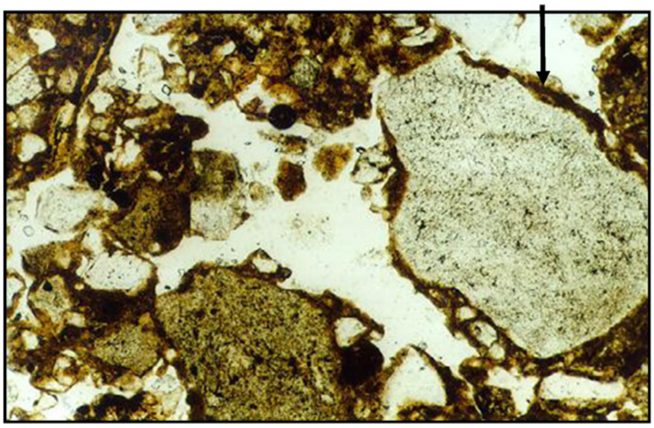

Fig. 3. Organic matter coatings are common on mineral grains in the fan alluvium of Zuni runoff fields (the arrow indicates one of the many coatings in this photomicrograph; frame length = 7 mm). Such organic matter additions function to build and renew the fertility of agricultural soils.

In addition to increased water-holding capacity with thicker soils, actual soil moisture increases have been measured in Southwest terraced fields and in other agricultural rock features such as in Chihuahua, the lower Verde Valley (Fig. 4), Safford, Mimbres, and northern New Mexico (Dominguez, 2002; Herold, 1965; Herold and Miller, 1995; Homburg and Sandor, 1997; Homburg et al., 2004; Lightfoot and Eddy, 1994; review in Sandor, 1995). Long-term increased moisture that essentially changes the climate factor of soil formation should result in higher soil weathering and formation rates. This has not yet been carefully studied in ancient Southwest agricultural contexts, but has been reported in some irrigated soils (e.g., Ricks Presley et al., 2004). Slightly more leaching of carbonates and corresponding pH decrease have been observed at Zuni and elsewhere. Soil temperature moderation has been documented in rock mulch fields (Lightfoot and Eddy, 1994). Soil environments altered by sedimentation, soil thickening and accompanying soil texture change, increased moisture levels and storage capacity, thermal, snow trapping and other microclimate changes in rock feature fields, etc., may lead to long-term soil transformations.

In contrast to enhancement, it is likely that terracing was originally an adaptive response to accelerated erosion from farming hillslopes with insufficient erosion control (Sandor, 2006). Innovations such as the "splash pads," semi-circular rock aprons constructed at the downslope base of terrace walls in the Safford area (Neely, 2001), appear to have provided additional protection to soils to prevent undercutting and piping erosion, a common negative side effect of terracing, especially in fields that are abandoned or otherwise not maintained.

Increased surface soil thickness and texture change can result even more indirectly from soil management, for example from deposition of sediments transported in irrigation canals (Dart, 1986; Huckleberry, 1992). Deposition of suspended load in irrigation water is often viewed favorably to enrich and replenish soils (Castetter and Bell, 1942, 1951; Doolittle, 2000, 2006; Fish, 2000; Forbes, 1906). However, the potential risk of this process is excessive sedimentation that can compromise canal grade and clog canals (e.g., Dart, 1986; Forbes, 1906) and reservoirs (e.g., the inferred function of curved intakes to trap sediment before reaching reservoirs such as at Mesa Verde—Doolittle, 2000; Rohn, 1963), or bury crops during the growing season (Hubbell and Gardner, 1950). This illustrates the point that whether soil and landscape change is favorable or detrimental can depend on context and timing, as well as on the magnitude of the change.

Investigations of ancient rock mulch soils indicate a number of positive effects on soil quality. Relative to uncultivated controls, ancient rock mulch soils in central and southern Arizona functioned to enhance fertility, increase infiltration rates and moisture retention, reduce erosion, and protects crops from predation by burrowing animals. Other functions of rock mulch, ones that are especially important in areas with shorter growing seasons such as upland field systems of northern New Mexico, are increased heat retention, protection against frost damage, and accelerated seed germination and crop growth. Rock mulch fields in the lower Verde River valley, Safford Basin, and upper Queen Creek watershed have a number of properties that favor crop production (Homburg and Sandor, 1997; Homburg et al., 2004; Homburg, 2010). Relative to the control/terrace soils, rock mulch soils tend to have elevated organic matter and nutrients (especially nitrogen and phosphorus) levels. They also have increased water infiltration rates, as shown in Fig. 5. Salinity levels, though elevated in the rock mulch features, are far below levels that could have a detrimental effect on crop production. The rock mulch features promote fertility and moisture retention by armoring the soil and blocking direct sunlight on the soil surface, thus reducing

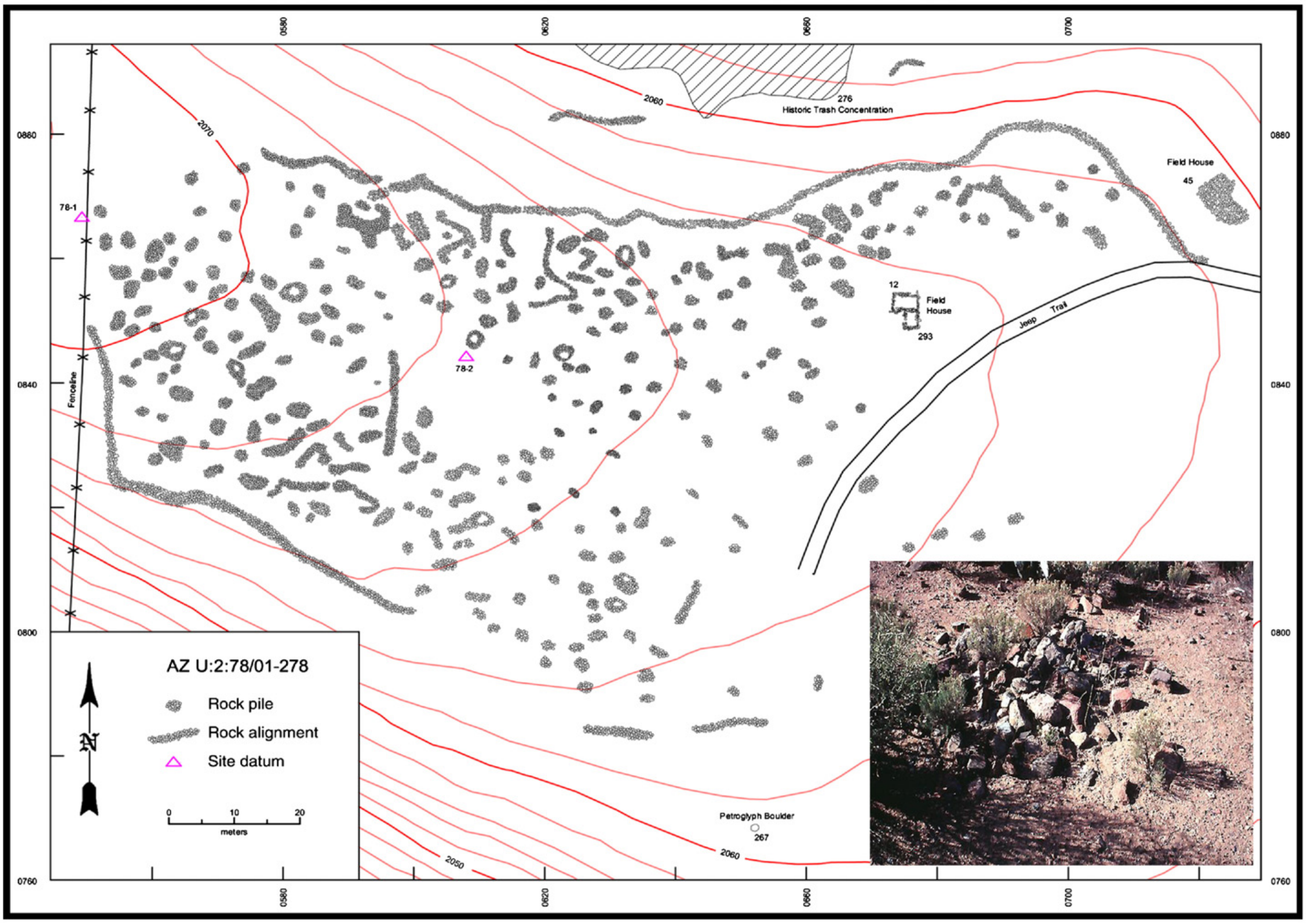

Fig. 4. Map of rock pile field in the lower Verde River valley (contour interval = 2 feet). Rock piles (see example in photograph) functioned to increase water infiltration and conserve soil moisture and nutrients in the root zone and rock alignments controlled runoff within the field system (see Homburg and Sandor, 1997). Drought-tolerant crops such as agave were cultivated in rock pile fields of central and southern Arizona.

evaporation of soil moisture and oxidation of organic matter. Soil data indicating elevated productivity in rock mulch soils is further bolstered by the fact that plants growing today are concentrated in the rock mulch soils. This observation indicates that these archaeological features continue to function today by promoting denser and more vigorous plant growth for centuries after the field system was abandoned by ancient peoples.

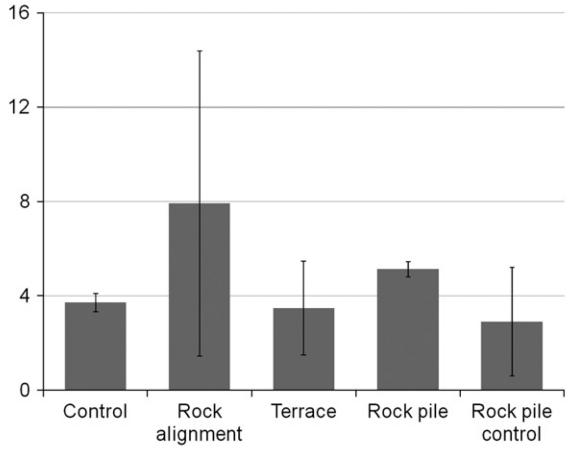

Fig. 5. Infiltration rates of rock mulch soils in the upper Queen Creek watershed of central Arizona are significantly higher than terrace and uncultivated control soils. Unsaturated hydraulic conductivity (mm/min) was measured using a tension infiltrometer at the −2 cm tension level. Bars are means (lines within bars show ± 1 standard deviation) for prehistoric rock alignment, rock pile, terrace, and uncultivated control soils in a dryland field complex (Homburg, 2010).

In contrast to the positive physical soil changes brought about deliberately through runoff and sediment management, there is less evidence for management practices that directly led to improved soil chemical and biological properties. A key factor is that direct addition of fertilizers or amendments is a rare indigenous practice in the Southwest (review in Sandor, 1995), in contrast to some other regions in the Americas such as Peru (e.g., Sandor et al., 2006). However, additions of sediments and organic debris in runoff indirectly increased soil fertility with nutrient additions, for example in historic and contemporary traditional runoff agriculture of the Tohono O'odham (Nabhan, 1984) and Zuni (Norton et al., 2007; Sandor et al., 2007). Soil pH changes detected in some Southwest fields, likely associated with the hydrologic effects of rock features, enhanced soil productivity by increasing availability of nutrients such as phosphorus through decreased alkalinity or acidity (Homburg and Sandor, 1997; Homburg et al., 2004; Sandor et al., 1990; Sullivan, 2000). Only a few studies of soil biology related to traditional Southwestern agriculture have been done, dealing with bacteria populations, nitrogen fixation and mineralization, and mycorrhizal fungi (Berry, 1995; Hubbell and Gardner, 1950; Sandor et al., 2007), but thus far almost nothing directly on soil biological change. Soil biology research would improve understanding of the effects of agriculture and management practices, such as nutrients in runoff (Norton et al., 2007), nitrogen-fixing crops like beans, and the role of mycorrhizae in improving traditional crop nutrition and water uptake. At Zuni, higher mycorrhizal fungi infection rates in Zuni blue maize compared with commercial hybrid maize imply important linkages of traditional cultivars to their local soils (Havener in Sandor et al., 2007: Table IV).

3.2. Soil degradation

Soil degradation encompasses those changes that result in decreased productivity and resource conservation. Degradation takes many physical/morphological, chemical, and biological forms (Johnson and Lewis, 1995). Common physical forms of degradation inferred in the Southwest include accelerated water or wind erosion that results in loss of critical surface horizons, and soil structural degradation and compaction that restrict root growth and compromises key soil functions involving physical support, nutrient and water storage and availability, infiltration, and aeration. Unfavorable soil chemical change in Southwest agriculture primarily involves nutrient and organic matter loss. There is also the possibility of salt and/or sodium accumulation in irrigated soils, which, while definitely a common problem in modern irrigation agriculture in the western U. S. and other arid world regions, has not been definitively documented in ancient Southwest agricultural soils (see next section).

Evidence of long-term accelerated water erosion has been observed at ancient agricultural sites in the Southwest. In one case former fields of the Santa Rosa Valley are so severely eroded that informants in the modern community of Ak Chin claim that erosion caused abandonment of that field system centuries earlier, after which their village was resettled in its present location on the Tohono O'odham Nation (Homburg and Casey, 2007). Another example is provided by some Mimbres agricultural terraced fields, where sheet rill and gully erosion contrasts with surrounding reference uncultivated surfaces lacking such erosion (Sandor et al., 1990). It is hypothesized that accelerated erosion and related soil degradation of the Mimbres fields persists nearly nine centuries after abandonment in part due to continued unstable surface conditions and exposed soil following loss of the original grass cover. Evidence that erosion commenced during prehistoric cultivation is that terrace dams are breached by gullies and that repair of damage was attempted by building rock dams within gullies. Over the greater Southwest, arroyo incision has been an episodic problem. There is controversy about natural climate-related versus anthropogenic land use causes, though it seems likely that land use problems such as deforestation and overgrazing are important factors that contributed to historic gullying. One of the negative consequences of gullies at Zuni and elsewhere is hydrologic bypassing of alluvial fans, which disrupts ecosystems and traditional runoff agriculture (Norton et al., 2007). Besides water erosion, damaging wind erosion accelerated by cultivation is thought to have occurred on volcanic ash fields in northern Arizona, as inferred from rock features interpreted as windbreaks (Doolittle, 2000: 239).

Soil structural degradation and compaction have been reported in several areas, such as Mimbres (Sandor et al., 1990), northern Arizona (Edwards, 2002), and certain areas at Zuni (Homburg et al., 2005). Structure degradation is signaled by loss of granular structure, weaker structure grade, and tendency toward larger aggregates (peds) and massive condition. Compaction, measured by increased bulk density, often accompanies structural degradation as soil porosity and pore size are reduced through physical compression and decreased organic matter (Fig. 6). In the Mimbres study, bulk density increased about 9% relative to uncultivated soils and may not have been a major problem, but that degree of compaction has been shown in experiments to inhibit maize seedling development and root elongation, especially in fine-grained soils.

Losses of organic matter and nutrients have been reported in widespread areas of the Southwest, such as in the Mimbres area already discussed, northern Arizona (Berlin et al., 1990; Edwards, 2002), and the northern Rio Grande (Arrhenius, 1963). The Mimbres research indicated consistent, statistically significant and substantial losses of organic carbon, nitrogen, and total phosphorus, not only in A horizons, but also extending into subsurface horizons (Sandor et al., 1990). Fig. 7 clearly shows the pattern of nitrogen loss in the Mimbres fields compared to uncultivated controls and runoff sediment (Fig. 7). This long-term degradation is attributed to the sensitivity of soil and ecosystem to disturbance; i.e., to low resilience. Major mechanisms of soil organic matter loss involve greater rates of microbial decomposition of organic matter with cultivation and subsequent exposure and oxidation of organic matter previously protected within aggregates, as well as decreased inputs of organic matter with less vegetation cover (McLauchlan, 2006). Lower nutrient levels relate to lower organic matter and also to crop removal of nutrients with harvesting and decreased nutrient inputs. Organic matter and nutrient losses can be offset in some areas by organic debris and nutrient inputs in well-managed functioning runoff systems, but that balance was apparently not achieved in the Mimbres situation, especially where accelerated erosion was more intense. Lower nitrogen in Mimbres cultivated soil was reflected in reduced maize growth and nitrogen content in a greenhouse experiment comparing cultivated and uncultivated soils (Sandor and Gersper, 1988).

Persistence of soil degradation centuries after abandonment is also remarkable in that decreased levels of organic matter (up to about 45% loss), nitrogen (about 40% loss), and phosphorus (about 18% loss) on a mass concentration basis in surface horizons are in line with losses reported for many soils under modern conventional cultivation (McLauchlan, 2006; Sandor and Eash, 1991). These similarities show the relevance of ancient agricultural sites for agriculture today in extending the time perspective on how long degradation can persist without appreciable recovery. The Mimbres case also illustrates the important linkage of long-term soil degradation to landscape erosion processes and reduced vegetation cover (Sandor et al., 1990). Landscape stability and restored vegetation, especially grasses in the case of Mollisols, are critical to soil recovery processes (McLauchlan, 2006).

Based on the known importance of organic matter in maintaining soil structure and lower bulk density, it is likely that the compaction of Mimbres agricultural soils is linked to organic matter decline. Whereas uncultivated soils have a wider spread of values that show the expected inverse relationship between bulk density and organic carbon, values in degraded cultivated soils cluster around lower organic carbon levels and higher bulk densities. The reduced variability in bulk density and organic matter and nutrient levels in these cultivated soils illustrates the connection between degradation and loss of diversity.

Nearly all soil degradation is unintended. A rare exception is the deliberate erosion of soil from a watershed to promote sedimentation in fields downslope. This practice has been documented in central Mexico and some other regions such as the Philippines, but not thus far in the Southwest (Doolittle, 2000; Sandor, 2006; Wilken, 1987).

Soil degradation in the Southwest has likely accompanied other kinds of environmental resource degradation, such as forest depletion (e.g., Kohler, 1992). A question of major interest is whether soil degradation was severe enough to be a causal factor in population abandonment or movement, which occurred commonly in the prehistoric Southwest (Cordell, 1997; Nelson and Hegmon, 2001). The question remains open, but the consensus from most soil studies conducted so far suggests that while soil degradation may have led to local abandonment and shifts in use of agricultural sites, it was probably not a major driver of regional abandonment.

3.3. Uncertain or minimal net soil change

In the majority of studies of soil productivity in the Southwest, definitive evidence of either positive or negative soil change is not apparent. Rather, results of studies are commonly mixed or inconclusive.

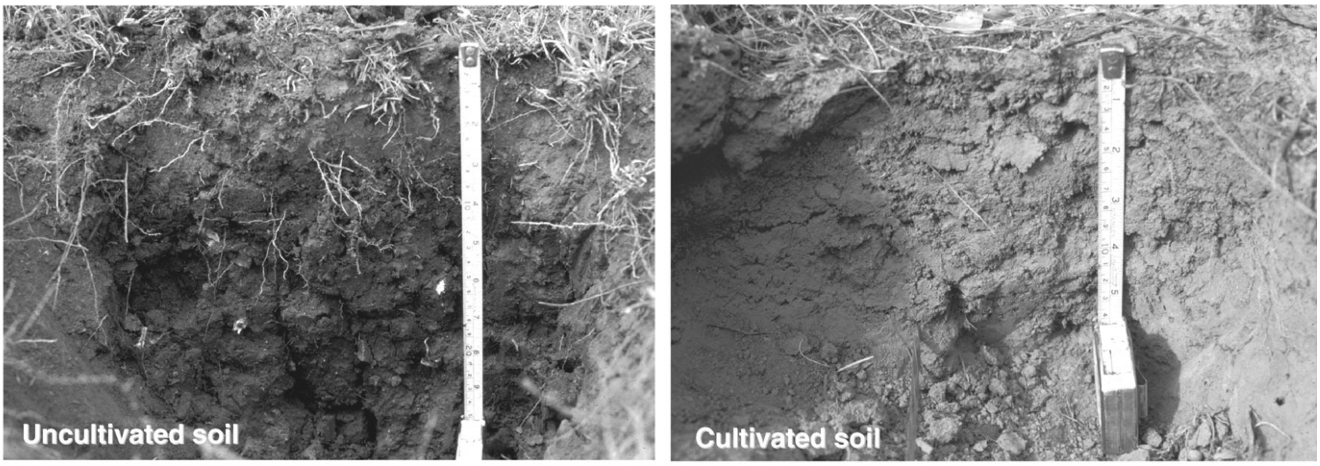

Fig. 6. Comparison of uncultivated soil (left) and Mimbres prehistoric agricultural soil (right). Soil degradation of the cultivated soil is indicated by compaction and lower levels of organic matter, as shown by its more massive structure and lighter color.

A relevant adage, attributed to Carl Sagan, is that "absence of evidence is not evidence of absence." Several possible reasons for uncertain outcomes are: (1) methodological constraints such as unavailability of reference sites for clear comparisons, or insufficient sampling (in extent and/or depth) relative to soil variability and scale; (2) post-agricultural imprints of environmental change or land use that partially or wholly obscure soil change; (3) soil changes that are not necessarily negative or positive, or that can be either under different circumstances (e.g., sedimentation); and (4) minimal overall net effects of agriculture, offsetting effects, or effects too subtle or ephemeral to define a clear direction of change.

The latter scenarios are plausible in that many Southwest agricultural systems are relatively subtle and have left a light environmental "footprint." For example, many ancient fields with rock alignments or other rock arrangements, in tandem with areas cleared of rocks, can blend in well with the natural landscape. Field configurations can nearly mimic those produced by natural geomorphic and watershed processes, such as alignments of rock fragments and wood that occur naturally as debris dams, or patches of rock concentrations and clearings. In contrast to more substantial to monumental agricultural features and soil construction and change in other world regions, much of traditional Southwest agriculture represents an inherently more low key enterprise in making use of natural landscape processes and ecosystems with slight modification, resulting in relatively minor soil change.

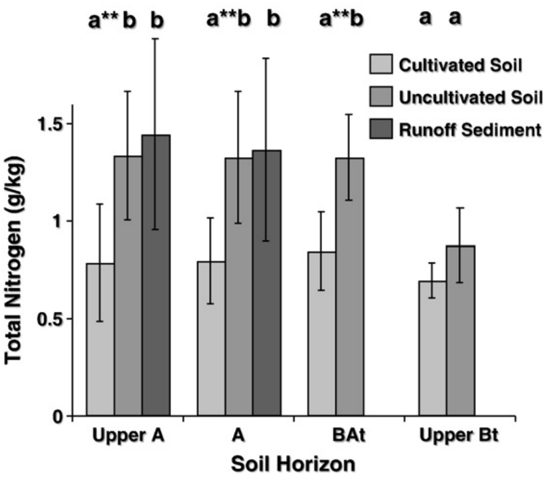

Fig. 7. Comparisons of total nitrogen in uncultivated and Mimbres prehistoric agricultural soils indicate soil degradation. Bars are means (lines within bars show ±1 standard deviation) from prehistoric cultivated soil, uncultivated soil, and recent sediment deposit sample groups. Double asterisks indicate significant overall differences among sample groups at the 0.01 probability level; different letters indicate individual mean differences at the 0.05 probability level (see Sandor et al., 1986 for details on statistical analyses).

Internal complexity within agricultural landscapes is also a factor in that some areas or niches may display degradation, while others may not. Even how values of soil properties are expressed can be variable in direction. For example, soil organic carbon or nutrients expressed on a mass/mass concentration basis could show a direction different than if expressed on a total mass/volume basis if there are differences in soil horizon thickness or bulk density. In the Mimbres case for instance, organic carbon, nitrogen, and phosphorus losses that are apparent on a mass or volume concentration basis to equal depths, are offset when total A horizons of cultivated and uncultivated soils are compared on a volume basis because of soil thickening from terracing and sedimentation.

Several studies of rock feature systems show mixed or equivocal findings regarding existence or direction of change in soil fertility and environmental resource condition. In the lower Verde Valley (Homburg and Sandor, 1997), comparisons of terraced soils with controls indicate lower organic carbon and nitrogen, but greater phosphorus. Comparisons involving other rock alignments and rock piles show both nutrient increases and decreases, so distinctive overall trends are not evident. Comparisons of rock grid, rock pile, and terraced soils with control soils at Safford also produced mixed results, though significant intrasite differences between rock alignments and rock-cleared field interiors were found (Homburg et al., 2004). Along with little change in bulk density, results here suggest that agriculture did not degrade soils, at least not in the long-term, and pH decrease increased availability of some nutrients such as phosphorus. Other possible confounding factors may be at work here, for example this agricultural system likely emphasized production of desert plants such as agave rather than more standard agronomic crops such as maize (Fish et al., 2004). Also, post-agriculture vegetation patterns associated with rock feature fields may cause soil differences (Briggs et al., 2006; Fish et al., 2004).

Some variable results from the Zuni case study illustrate complexities involved in soil studies, such as how different sample designs can lead to different results, as well as actual multiple outcomes depending on site and time factors. Results of the extensive sampling and comparison of currently cultivated, abandoned, and historically uncultivated soils essentially indicate no net change in soil organic matter or nutrients nitrogen and phosphorus, nor significant compaction (Homburg et al., 2005). Measured soil changes seem to mainly relate to runoff agriculture, for example in consistent A horizon thickening patterns. Another runoff agriculture-related trend is distinct associations of silt and organic matter preferentially co-transported and deposited with runoff, as seen in regression analyses of silt and nitrogen and micromorphological studies showing distinctive organic matter coatings on mineral grains in soils of runoff fields (Sandor et al., 2007). However, intensive paired site studies comparing long-term contemporary fields with adjacent historically uncultivated areas with native grass and shrub vegetation indicate locally significant differences. In some intensive site comparisons, organic matter decrease and bulk density increase are evident, while other comparisons do not show these trends. In all cases studied thus far, degradation seems more associated with modern tillage in the ancient fields rather than traditional agricultural techniques (Sandor et al., 2007). An observation of a current traditional field recently severely damaged by wind-erosion following deep plowing also illustrates negative impacts from intensive modern tillage. In contrast, an observation of maize nitrogen deficiency (chlorosis symptoms) in a traditional Zuni runoff field cropped for several years, compared with green vigorous maize in an adjacent new field, indicates that declines of fertility are ephemeral when fallowing is practiced in traditional runoff fields. The overall results of Zuni soil studies point to overall sustainability of traditional agriculture but some degradation with modern cultivation.

The question of salinization problems in traditional irrigated agriculture remains open and illustrates uncertainty in soil change and interpretation in the Southwest. Cases of detrimental levels of salt and sodium accumulation caused by irrigation are well-known in modern agriculture (Szabolcs, 1998), though scientific documentation is surprisingly rare. In some areas, excessive salt and sodium accumulation has led to abandonment, or at least severe limitations on use and choice of crops. Examples of significant soil degradation have also been reported for ancient cultures in other arid regions, such as Mesopotamia and central Asia (Hillel, 2008; Szabolcs, 1998). Prehistoric farmers in the Southwest probably contended with naturally occurring saline and sodic soils. These soils, and their occurrence in and around prehistoric, historic, and contemporary American Indian irrigated fields, have been documented in several areas of the Southwest: especially in the lower deserts in the Hohokam area along the middle Gila River (Castetter and Bell, 1942), and also in limited areas of the northern Rio Grande Valley, the Colorado River in the Grand Canyon (Davis et al., 2000), the lower Colorado and Gila Rivers (Castetter and Bell, 1951; Doolittle, 2000), and on other valley floors such as at Zuni. Davis et al. (2000) argue that high salinity measured at one early irrigated site in the Grand Canyon was induced by irrigation. Salinization has been identified in probable Akchin floodwater fields in the Santa Rosa Valley of the Tohono O'odham Nation (Homburg and Casey, 2007). Soils mapped by the Natural Resources Conservation Service (USDA-NRCS, 1998) in the Hohokam area as saline or sodic are likely to have been that way before prehistoric irrigation, as indicated by well-developed soil features that take significant time to form, such as natric horizons. Naturally salt-affected soils likely dictated where irrigated agriculture could best be practiced (Castetter and Bell, 1942, 1951). Other lines of evidence such as ostracods in Hohokam irrigations canal sediments suggest some salinity, but not necessarily high levels (Palacios-Fest, 1997). The jury is still out on whether prehistoric irrigation agriculture ever resulted in serious enough salt and/or sodium accumulation to the point of significant reduction in crop productivity. Some authors have indicated that the Hohokam irrigation did cause salinity problems (e.g., review in Ackerly, 1988; Diamond, 2005; Hackenberg, 1964) but there has been very little work on agricultural soils to test this assertion. Although evidence of short-term canal abandonment suggests the possibility of salinity problems, the fact that the Hohokam maintained irrigated systems for about 1000 years (AD 400–1450) suggests that either they did not encounter major salinization and/or were able to manage them (Ackerly, 1988; Castetter and Bell, 1942; Fish, 2000).

4. Conclusions — relevance of soil change for the present and future

Although significant knowledge about soil and landscape change in Southwest American Indian agriculture and its archaeological record has been gained, much remains unknown and uncertain. Major reasons are the relative scarcity of soil studies, methodological shortcomings, the complexity of agricultural systems and soils, and imprints of multiple land use and environmental change. Expanded research is needed on changes in soil hydrology and nutrients in both dryland and irrigated systems. Current advances in soil science research such as on dynamic soil properties and soil biology can be applied to ancient agricultural sites to further understanding of long-term soil condition and land use sustainability. More work is needed to link soils to crop production through long-term in-situ experiments coupled with observational studies of traditional farming (Muenchrath et al., 2002). Some data are available for major agronomic crops such as maize, but less is known about soil function in relation to desert crops like agave. There is a need for soil-crop experiments on agricultural rock features, especially those that are little known ethnographically such as rock piles, grid, and mulch fields, as well as fields in volcanic tephra. More integrated watershed-field-soil-crop research is needed to understand the dynamics and impact of runoff agriculture in different ecosystems. Interdisciplinary collaboration in archaeology, soil and other earth and environmental sciences, and agricultural sciences, drawing on multiple lines of inquiry and evidence, is critical to addressing these needs and advancing understanding of soil and landscape change. Knowledge of long-term soil change under traditional Southwest agricultural systems is relevant to present-day critical resource issues on regional and global scales, such as climate change and variability, and related problems of water supply and use, and desertification.

Soil is a vital natural resource that past and present societies have relied on for their sustenance. Agriculture's impact on soils is complex in process and outcome, ranging from degradation in varying degrees and duration, to enhanced productivity and ecosystem function, as well as cases where outcomes seem minimal or uncertain. Soil is vulnerable to degradation that compromises its function and quality, and lowers crop productivity. Soil degradation continues to be a serious threat in the U.S. and throughout the world (Diamond, 2005; Hillel, 2008; Johnson and Lewis, 1995; Montgomery, 2007; Redman, 1999; Sandor et al., 2005). The long-term record of soil use and change by humans provides perspectives important to advancing sustainable agriculture and land resource conservation.

With some notable exceptions (e.g., terra preta soils in the Amazon Basin, plaggen soils in Europe, some ancient terraced soils in Peru and soils of Asian rice production systems), soil degradation is the most common outcome of agriculture on a world-wide basis (especially that caused by accelerated erosion, nutrient loss, and salinization), and similar outcomes are represented in the Southwest. Unlike many other parts of the world, it is interesting to note that numerous examples of soil enhancement are represented in agroecosystems of the Southwest. The American Southwest, with its long agricultural history and wide range of systems, environments, and effects, holds valuable evidence and lessons on soil and landscape change.

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